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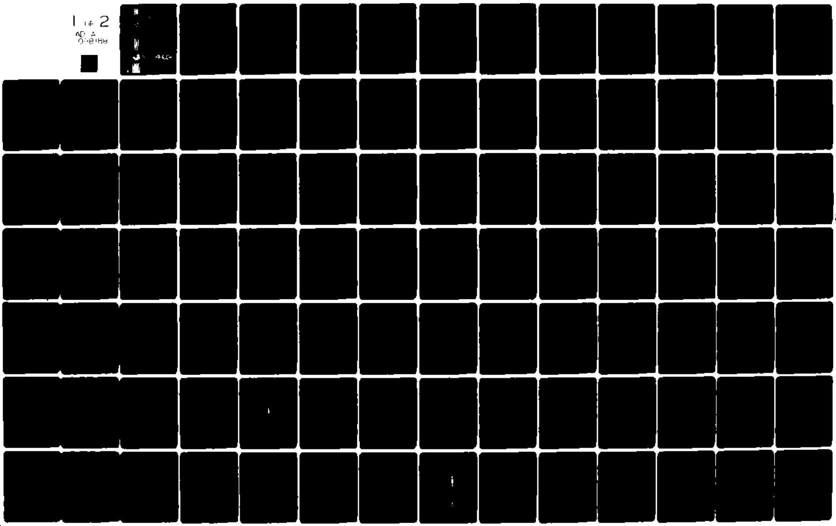

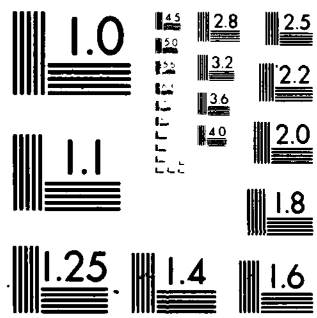

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NEW CONCEPT STUDY FOR REPAIR OF BOMB DAMAGED RUNWAYS

VOLUME I : CONCEPT IDENTIFICATION

SOUTHWEST RESEARCH INSTITUTE
SAN ANTONIO; TX 78284

SEPTEMBER 1979

FINAL REPORT
MAY 1977 — JULY 1978

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An in-depth review of bomb crater repair processes and material resulted in the identification of twelve concepts. Each concept is a general solution to the problem of crater repair which is amenable to implementation using numerous combinations of fill and cap materials. In addition to the study and description of repair processes, an in-depth review of alternate runway strategies is presented.

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PREFACE

This report was prepared by the Southwest Research Institute, San Antonio, Texas 78284 under Contract No. F08635-77-C-0154 with the Air Force Engineering and Services Center, Tyndall Air Force Base, Florida 32403. This work was begun on 1 May 1977 and completed on 15 October 1979.

This report consists of two volumes. This is Volume I which covers work from 1 May 1977 to 24 July 1978.

This report has been reviewed by the Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

Michael T. McNerney
MICHAEL T. MCNERNEY, Capt., USAF
Project Officer

Robert E. Boyer
ROBERT E. BOYER, Lt Col., USAF
Chief, Engineering Research Div.

George D. Ballentine
GEORGE D. BALLENTINE, Lt Col, USAF
Director, Engineering and Services
Laboratory

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TABLE OF CONTENTS

TABLE OF CONTENTS (Concluded)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Concluded)

LIST OF TABLES

LIST OF TABLES (Concluded)

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SECTION I

INTRODUCTION

A. Purpose and Scope

The purpose of this phase of the program was to develop concepts for the repair of bomb damaged runways at U.S. Air Force bases. The runways at these bases would be a prime target in the event of hostile action by an enemy. This has always been the case in modern warfare; however, since hardened shelters are widely used to protect the aircraft, the runway has become the number one target at a forward air base. For this reason, it is important that the base Civil Engineer be equipped and able to execute a bomb damage repair (BDR) in a minimum period of time.

The program to develop improved BDR concepts was divided into three phases. The first phase involved the review of the large volume of literature related to the subject of bomb damage repair. A separate report summarizing this effort was submitted at the conclusion of the initial phase. Over 1000 abstracts were reviewed and screened and over 100 reports were reviewed in detail.

The second phase, which this report covers, involved the preliminary development of BDR concepts. Each concept was developed in sufficient detail to determine if the procedure had capability of meeting the criteria for the repair set forth in the contract. The most promising techniques were presented at the conference held at Tyndall AFB. At the conclusion of this conference, the Air Force selected four concepts for further development.

B. Technical Requirements

The ultimate goal of this project was to develop a BDR system which will allow immediate launch of tactical aircraft followed by expedient repair of a 50-ft by 5000-ft strip within one hour of an enemy attack. It was recognized that few, if any of the concepts would meet this goal, but the final concept selected must optimize the trade-offs between cost, practicality, and repair time.

There were a number of assumptions that were set forth in the contract to be considered during the project. These assumptions were as follows:

1. Types of Pavements to be Repaired -

Portland cement concrete, asphaltic concrete, or portland cement concrete with asphalt overlay were the types of pavements to be repaired. The portland cement concrete will not be continuously reinforced but may contain temperature steel. Consequently, repair concepts must be able to handle pavements with temperature steel.

2. Types of Aircraft Traffic -

F-4 and F-111

3. Damage Levels -

Three 750-lb bombs

Thirty 25-lb bombs

4. Types of Damage -

Spall, craters and camouflet

5. Minimum Acceptable Level of Repair

50 passes of either F-4 or F-111 aircraft

6. Maximum Level of Repair Required -

100 passes of F-4 or F-111 aircraft each day for two weeks

7. Acceptable Levels of Maintenance

Maintenance may be performed after each 50 passes if the time required does not exceed one hour.

8. Operational Environment -

Temperature range: -25°F to 125°F

Adverse moisture: Snow, sleet, and rain

9. Other Hazards

Unexploded bombs and mines

C. Operational Scenario

An operational scenario was developed during this phase of the project. The various tasks and subtasks involved in the BDR procedure are illustrated in Figure 1. All of the activities between the survey task and the painting of the new centerline of the repaired strip are considered as part of this program and are identified in Figure 1 as "Our Problem." As can be seen in the flow diagram, there are a number of different decisions and activities that will have to be completed in order to launch the aircraft off of a repaired surface. Some of this task includes the following:

- Survey
- EOD and Mine Clearance
- Deployment of Crews
- Debris Removal and Backfill Operation
- Repair Procedure or Technique Used
- Control of Aircraft Traffic.

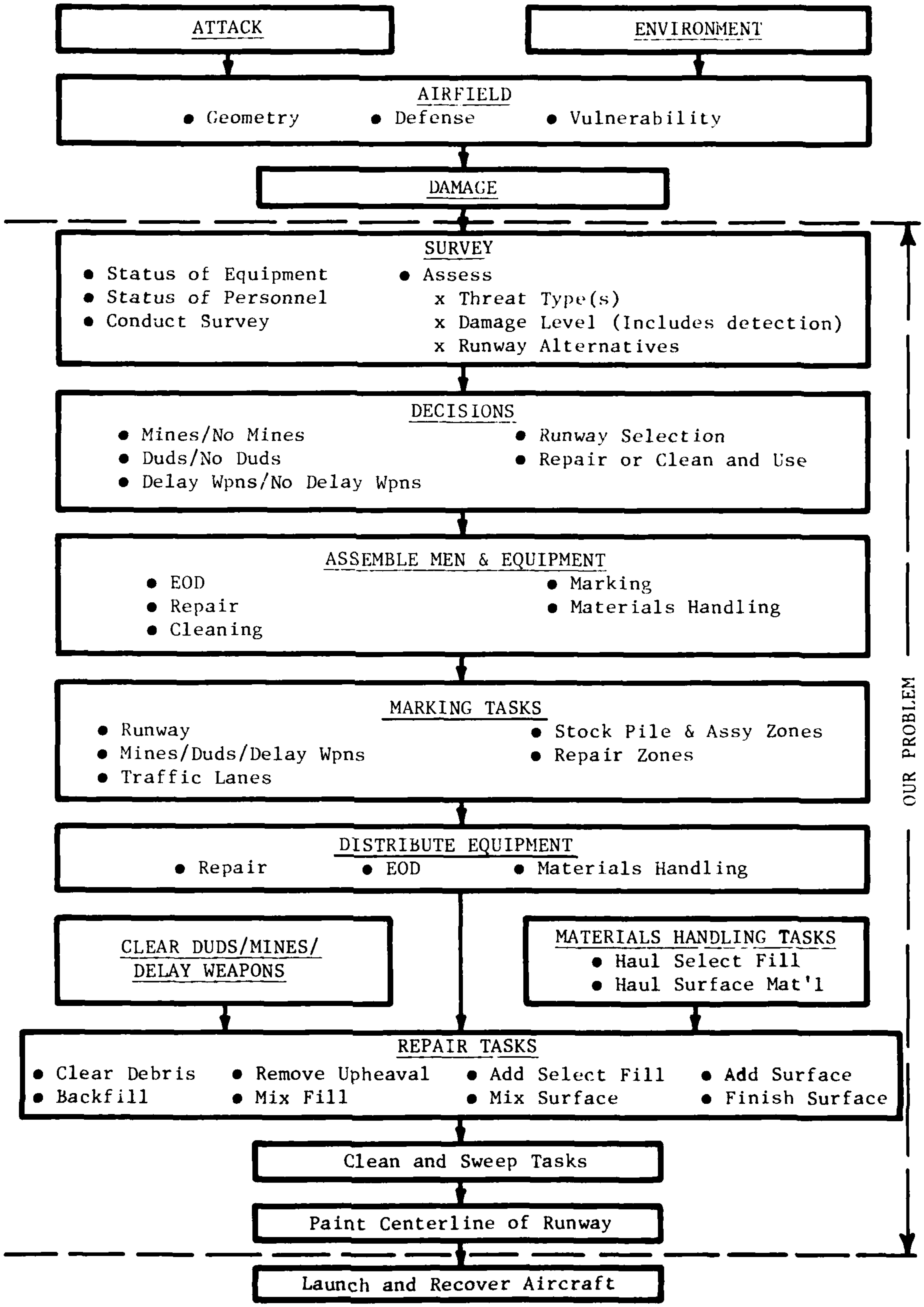


Figure 1. Operational Scenario

A number of these tasks will be discussed in this report. It was felt that the EOD and mine clearance problem was of such a nature that it should be treated in a separate companion report on this project.

D. Objective

The objective of this program was to develop in a preliminary way a number of concepts that could be used to rapidly repair a bomb damaged runway. At the conclusion of this phase, a conference was held at Tyndall AFB on June 1-2, 1978 to present the results of the first two phases and to select the four repair concepts to be developed in detail.

The remaining sections in this report discuss the various activities studied and the preliminary concepts developed.

SECTION II

TECHNICAL DISCUSSION

A. Current BDR Techniques

At the present time the recommended rapid runway repair procedure described in the Department of the Air Force Regulation 93-2 involves the use of AM-2 mats. The repair procedure requires approximately four hours to complete. A Program Review and Evaluation Technique (PERT) diagram of the activities associated with this repair procedure is presented in Figure 2. It is apparent from this diagram that there are a number of tasks that must be accomplished in less time if the goal of repairing a bomb damaged runway within one hour is to be approached.

An example of a PERT diagram for a one hour repair with the time allocated for the major task is shown in Figure 3. As can be seen by comparing the two PERT diagrams, some of the tasks will have to be done in 1/4 to 1/3 of the time presently required. This obviously indicates that the procedures, equipment, and/or techniques used to accomplish these tasks will have to be different. Three operational improvements which could significantly reduce the repair time were identified. These are as follows:

1. Store fill and repair materials adjacent to the runway. This reduces material handling time and equipment requirements for material transport.

2. Use larger equipment to remove debris/upheaval and to install the fill material. This increases the work applied to the task per unit time.

3. Eliminate or modify the way that the AM-2 mat system is assembled.

Another observation that was made by the contractor project team members was that, if debris is not used to fill the hole, about 550 cubic yards of material must be put into the crater produced by a 750-pound bomb and 400 cubic yards of debris must be removed. Whereas if debris is used, approximately 150 cubic yards of additional material must be used to fill the crater. Therefore, with the time constraint being what it is, debris must be used to help fill the crater.

B. Activities and Considerations

1. Runway Damage Assessment

One of the first tasks that must be completed after an airfield has been bombed is a survey of the damage. The results of this survey should indicate the extent of damage done to the runway and be used to select the area to be repaired. As can be seen in Figure 3, the task of surveying and selecting the repair strip to be repaired will have to be accomplished within the first 10 minutes of the effort in order to approach the goal of a one-hour repair time. As a result, the area chosen to be repaired may not be the optimum location from a viewpoint of minimizing the number of craters that will have to be repaired. However, sufficient data should be collected

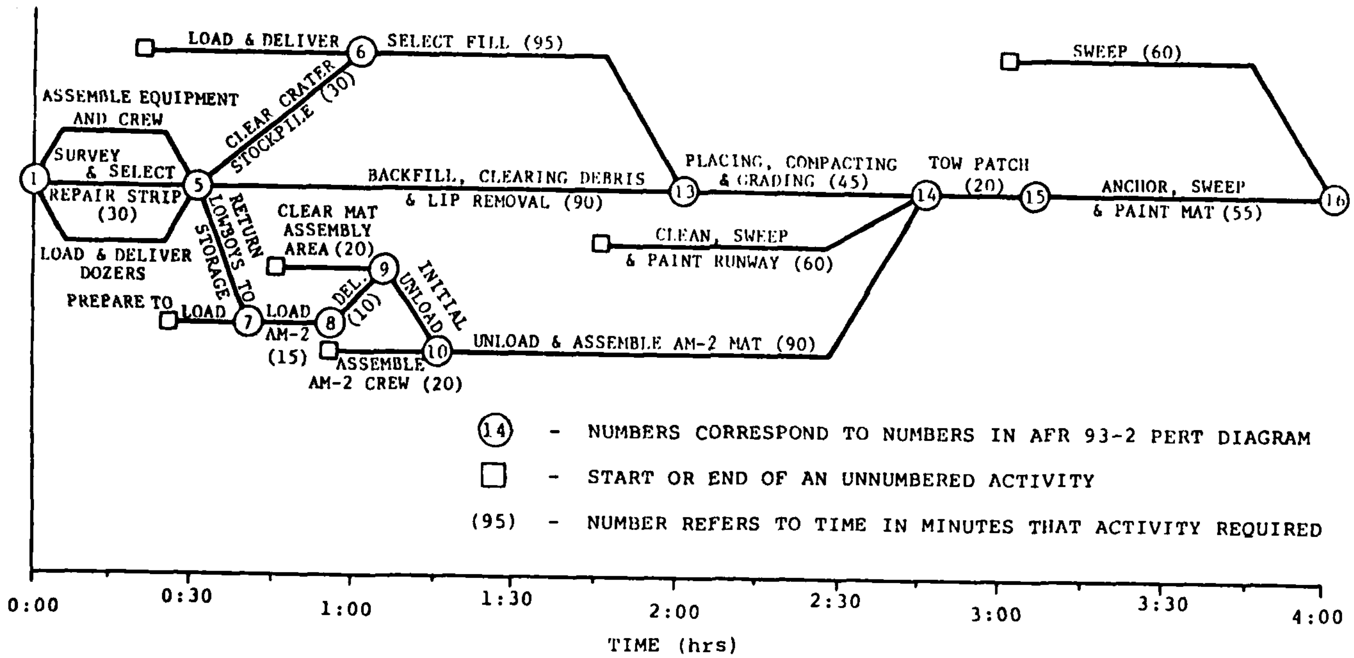


Figure 2. PERT Diagram for AFR 93-2

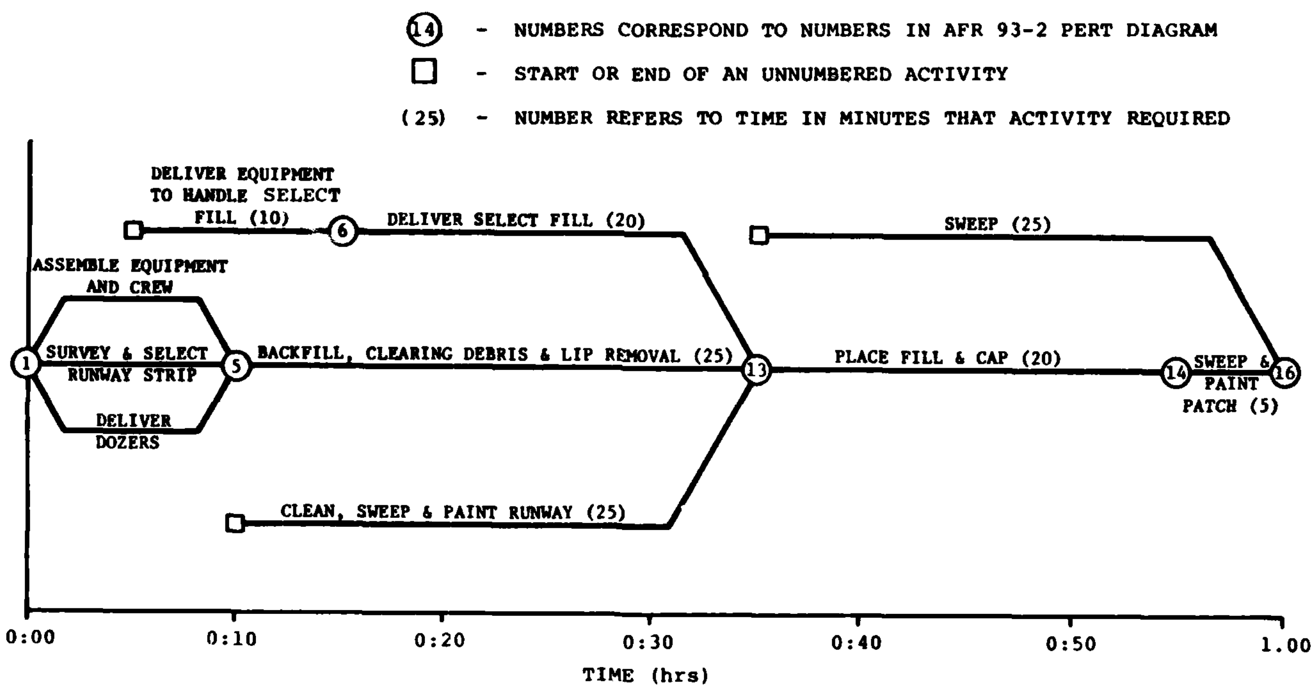


Figure 3. PERT Diagram for Example 1-Hour Repair

and supplied to the officer in charge of the repair so that he may be confident that the area that is chosen will be one of the best selections.

Thirteen different survey procedures were selected for evaluation on this program. The procedures considered were as follows:

1. Helicopter Launched Following the Attack

2. Helicopter Launched Before the Attack

3. Ground Survey - Jeeps (1-6) with Communication to Base Command Center

4. Ground Survey - Single Jeep with Decision Maker

5. Television - Helicopter Based

6. Television - Hard-Mounted at Selected Locations

7. Photography - Aerial Photography

8. Electronics - Preinstalled Grid System

9. Electronics - Direct Coded Computer System with Input from Helicopter Based Observer

10. Television - Remote Piloted Vehicle Based

11. Television - Balloon Mounted

12. Runway Grid System - Ultraviolet Markings

13. Ground Survey - Armored Vehicle with Communication to Base Command Center

Each of these concepts is briefly described in Appendix A.

The runway damage assessment (RDA) procedures were independently evaluated by six members of the contractor project team using the evaluation sheet shown in Figure 4. As indicated in the figure, six technical and five other considerations were evaluated. Each procedure was evaluated for its ability to satisfy the various considerations with a score of 5 being the highest value obtainable and 1 being the lowest. Each consideration was rated for its importance in the operation and given a Weighting Index (WI). A weighting index of 10 indicates a critical consideration, and a weighting index of 2 is of much less importance to the operation. The total value for each consideration was obtained by multiplying the score by the Weighting Index.

The total value for each procedure was summed, and an average of the six evaluations was tabulated to obtain a ranking of the various procedures.

After the first set of evaluations, five of the procedures were eliminated from consideration primarily because it was felt that none of these procedures could meet the time constraint allowance of 10 minutes for the survey and selection within the present state-of-the-art technology associated with each. These were the following:

RDA Concept # ________________ Evaluated By ____________________

TECHNICAL CONSIDERATIONS	SC	WI	TOTAL
1. Use of existing equipment and technology. None (1) 2 3 4 (5) Extensive		4	
2. Response time. >60 min (1) · 45-60 min (2) · 30-45 min (3) · 15-30 min (4) · <15 min (5)		10	
3. Effectiveness in darkness. Not Effective (1) 2 3 4 (5) Extremely Effective		8	
4. Effectiveness adverse weather. Not Effective (1) 2 3 4 (5) Extremely Effective		8	
5. Provides needed data on (None 1 – 5 Extensive) a. strafing (spall) 1 2 3 4 5 b. bomb damage 1 2 3 4 5 c. delayed ordnance 1 2 3 4 5 d. mined areas 1 2 3 4 5		10	
6. Damage locations. (None 1 – 5 Extensive) a. strafing (spall) 1 2 3 4 5 b. bomb damage 1 2 3 4 5 c. delayed ordnance 1 2 3 4 5 d. mined areas 1 2 3 4 5		10	
OTHER CONSIDERATIONS			
1. RDA team safety Extreme Exposure (1) 2 3 4 (5) Minimal Exposure		4	
2. Special skills required. Many Highly Skilled Personnel (1) 2 3 4 (5) No Highly Skilled Personnel		5	

Figure 4. Sample Runway Damage Assessment Evaluation Sheet

	SC	WI	TOTAL
3. RDA team training required. Extensive Training 1 — 2 — 3 — 4 — 5 No Training		5	
4. Development costs ($ thousands). >1000 (1) — 500-100 (2) — 250-500 (3) — 100-250 (4) — <100 (5)		2	
5. Installation and Operational costs ($ thousands per site). >1000 (1) — 500-1000 (2) — 250-500 (3) — 100-250 (4) — <100 (5)		5	

REMARKS:

Figure 4. Sample Runway Damage Assessment Evaluation Sheet (Concluded)

- Procedure No. 5 - Helicopter-Mounted Television. It was felt that it would be difficult to accurately scale the projected image on the TV screen for use with an interactive computer system unless some grids were added to the runway. With specific size grids, the computer operator should be able to estimate the relative size of each crater, however the collection and analysis of the damage data is expected to require longer than the allotted 10 minutes for the survey and selection task.

- Procedure No. 7 - Aerial Photography with Stereoscopic Interpretation. It was too time-consuming.

- Procedure No. 9 - Electronic-Direct Coding of Computer With Input From Observer Onboard Helicopter. It was too time-consuming.

- Procedure No. 10 - Television-RPV Based. Since all of the data used with this system would be transmitted via video data link, as opposed to a combination audio/video data link, it was decided that the runway would have to have an elaborate grid system so that the television monitoring crew would always be able to determine the exact location of the craters. If a typical alphanumerical system were used to identify each of the grids, it is anticipated that the large number of lines and identifiers could cause some confusion to the pilots during normal flight operations.

- Procedure No. 11 - Television-Balloon Mounted. Weather limitations affected this procedure.

The ranking of the other eight RDA procedures is presented in Table 1. Also presented in this table are several other features of each procedure. The RDA team safety is reported as a number between 1 and 10, with 10 representing the safest condition. A value for each concept was obtained by averaging the result of the voting by the six evaluators. Those concepts which require less exposure of the RDA team obviously score higher in this category.

<u>Response Time</u> in minutes is the time required by the RDA team to complete their survey and establish a centerline for the runway. The time periods reported in the table were arrived at as a result of the voting of the project team members based on their individual knowledge and experience.

<u>Percent Effectiveness in Collecting the Desired Data if the Mission is Completed</u> is a measure of the performance of the concept without regard to other aspects. Each number represents the percent effectiveness of that concept to collect information on the type and location of runway damage even during adverse weather and darkness.

<u>Probability of Completing the Mission</u> is based on the scores from the three previous columns: team safety, response time, and data collection. The ratings are qualitative. Negative aspects of the concept are indicated below the rating. For example, a concept may have a good probability of completing the mission, but the amount of time required is excessive so time would be indicated as a negative aspect.

TABLE 1. SUMMARY: EVALUATION OF RUNWAY DAMAGE ASSESSMENT CONCEPTS*

RANK	CONCEPT	RUNWAY DAMAGE ASSESSMENT TEAM SAFETY SCALE (1.0-10.0)	RESPONSE TIME (MINUTES)	EFFECTIVENESS (%)	PROBABILITY OF COMPLETING MISSION (NEGATIVE ASPECTS)	DEVELOPMENT, INSTALLATION, AND OPERATIONAL COST ($)	SPECIAL SKILLS AND TRAINING REQUIRED	DEVELOPMENT REQUIRED
1	Ground Survey - Jeep (1-6) with communiciations to command center	3.0	30-45	84	Poor (Safety)	<100K/<100K	Minimum	None
2	Ground Survey - Armored Vehicle with communications to command center	7.3	30-45	84	Fair (Time)	<100K/<1000K	Minimum	None
3	Electronic - Preinstalled grid system	10.0	<15	78	Good (Data)	500-1000K/ 500-1000K	Extensive	Considerable
4	Helicopter - Launched before attack	7.7	<15	73	Fair (Data)	<100K/>1000K**	Moderate	None
5	Helicopter - Launched after attack	8.3	15-30	73	Fair (Time, Data)	<100K/>1000K**	Moderate	None
6	Helicopter - In conjunction with runway grid system and ultraviolet markings	8.7	15-30	78	Good (Time, Data)	250-500K/>1000K**	Moderate	Some
7	Ground Survey - Single jeep with decision maker	2.7	>60	80	Poor (Safety, Time)	<100K/<100K	Minimum	None
8	Television - Hard Mounted at selected locations	10.0	<15	67	Poor (Data)	250-500K/ 500-1000K	Extensive	Some

*(1) The damage levels expected for this evaluation are up to three 750-pound bombs and thirty 25-pound bombs plus unexploded bombs and mines contained in the selected 50 feet by 5000 feet strip.

(2) The allotted time for the survey and selection of the 50 feet by 5000 feet strip to be repaired was 10 minutes.

** The operational costs of concepts 4, 5, and 6 would be extremely high because of the expense of a helicopter. The exact cost would have to be evaluated at a later date.

- Cost - Development/Installation and Operation

- Special Skills and RDA Training Required

- Use of Existing Equipment and Technology

These three categories are self-explanatory and do not affect the technical feasibility of the concept. In each concept employing a helicopter, the installation and operation cost reflects the total purchase and maintenance of the helicopter since the helicopter would be dedicated to Rapid Runway Repair (RRR).

The top ranking procedure, Ground Survey With 1-6 Jeeps, has a low RDA team safety and is time-consuming. The second ranked procedure, Ground Survey with Armored Vehicles, is safer but is still time-consuming. The third ranked procedure, Preinstalled Electronic Grid System, is safe and quick; however, it would require considerable development and would be very expensive.

The fourth ranked system, Prelaunched Helicopter With a Trained Observer on Board. is quick, relatively safe, and utilizes current state-of-the-art equipment and techniques; therefore, it appears that this procedure would be the best procedure for runway damage assessment. A flow diagram for a runway damage assessment scenario is presented in Figure 5.

a. Assemble Personnel and Equipment (Block 1)

Contingency plans for operations in the event of an attack must include the formation of an RDA team and allocation of equipment for their use. The RDA team would include at a minimum:

- Engineering Officer/Team Leader - The team leader would have responsibility for the overall RDA effort and would make the final selection of the emergency runway location. He must be thoroughly familiar with base facilities, runway construction, and the runway requirements of the aircraft using the facility. This officer must have the experience and authority necessary to select the emergency runway location immediately upon his evaluation of the damage, as observed during the RDA flight. The RDA team leader could be the Base Civil Engineer, a member of his staff, or the OIC of the RED HORSE/Prime BEEF detachment on base.

- Helicopter Pilot - The pilot would be responsible for seeing that the helicopter was at the assembly area at the time of an alert and for flying observation missions as required during RDA efforts. A co-pilot or crew chief may also be included in the crew.

- Recorder/Observer - The recorder/observer must be familiar with the base runway layout, the location of repair equipment and supplies, and the survey maps used during the RDA survey. He will be responsible for observing and recording bomb damage and mined areas on the survey map during the RDA activity and assist in determining the emergency runway centerline. A minimum of one recorder/observer is required; two are recommended.

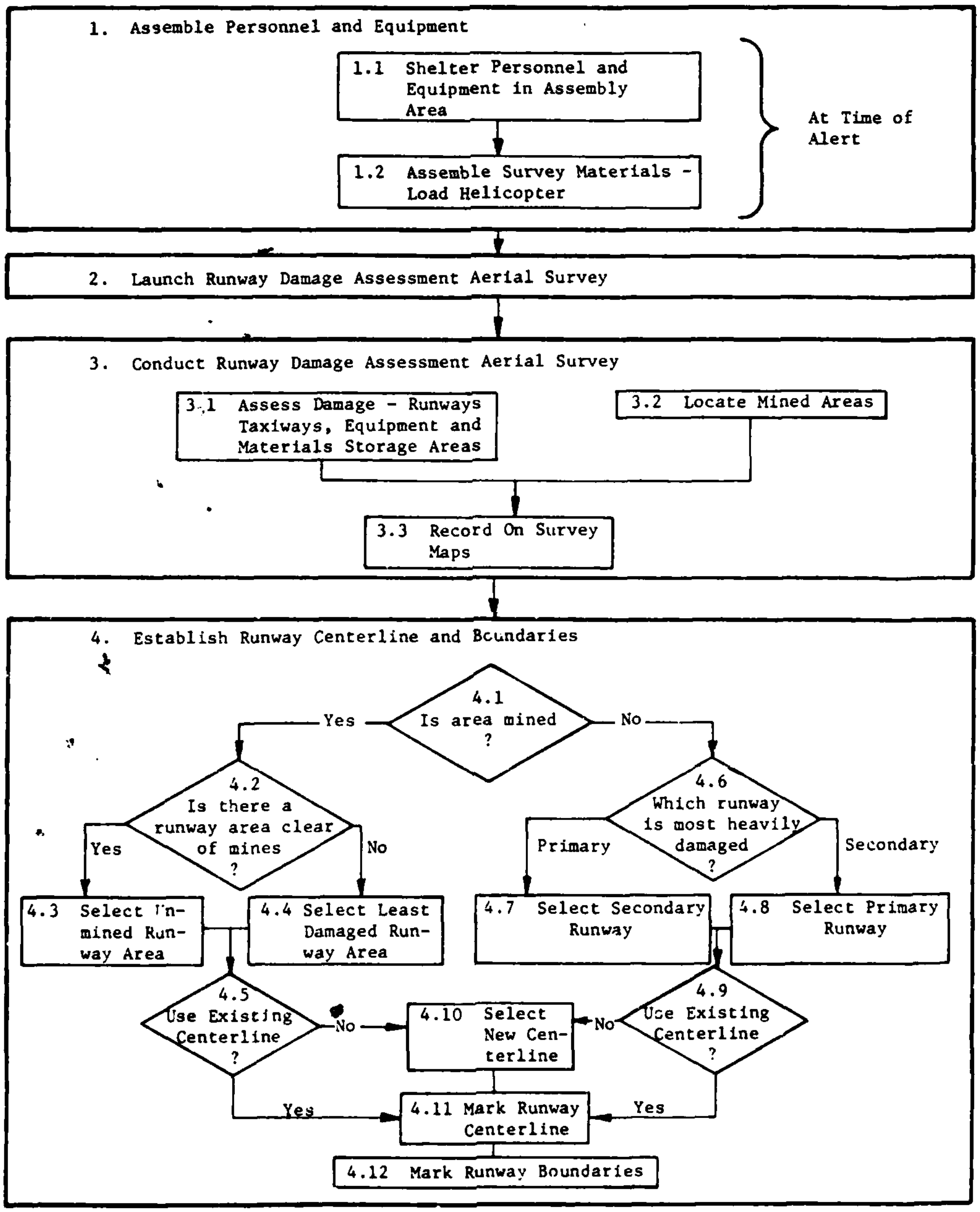


Figure 5. Runway Damage Assessment Scenario

Equipment required to support the RDA activity includes:

- Helicopter - The helicopter for the RDA activity must provide space for three to five personnel, plus sufficient room to record damage and mine data on the survey map. It should be equipped with downward facing lights for nighttime observation and a launcher for dye markers. Secure voice communication from air to ground may also be necessary.

- Survey Maps - An accurate scale map of the runway area must be available for recording bomb damage and determining the location of the emergency runway. The map should contain a grid coordinate system which can be easily communicated by radio to EOD, mine clearing, and repair crews on the ground. It is recommended that runway length be permanently marked on each runway every 100 feet (from the prevailing upwind end), and these markings should be reflected on the survey map. At least two copies of the map should be available to the RDA team; copies must also be provided to the EOD, mine clearing, and runway repair crews.

- Runway Template - A template should be constructed of plastic or other material which reflects the size of the emergency runway (50 feet x 5000 feet) to the scale of the map. This template will be used by the team leader and observer/recorder to determine the best fit of the runway, considering existing bomb damage and mined areas.

The procedure for accomplishing the task illustrated by block 1 of the figure would be as follows:

Block 1.1 - Shelter personnel and equipment in assembly area - Upon alert of an impending attack, the RDA team will report to a predesignated assembly area. The needed equipment should be stored at the area on a permanent basis; the helicopter should be flown to the area and sheltered prior to attack. The assembly area should be the same as that used by the mine clearing, EOD, and runway repair crews.

Block 1.2 - Assemble survey materials, load helicopter - During or immediately after the attack, the materials should be retrieved from storage, checked for completeness, and loaded in the helicopter.

b. Launch Runway Damage Assessment Aerial Survey (Block 2)

This block is self-explanatory; once the ALL CLEAR signal has been received, the helicopter and crew will take off and begin the survey. The shelter for the helicopter should have enough vertical clearance to allow the craft to become airborne prior to leaving the sheltered area. In this manner, mines or bomb damage in the assembly area will not impede RDA activities.

c. Conduct Runway Damage Assessment Aerial Survey (Block 3)

The purpose of this task is to determine the extent and location of damage to the runway system so that the best location for the emergency runway can be determined.

Block 3.1 - Assess damage - runways, taxiways, equipment, and materials storage areas - Through a series of passes over the runway system, the RDA team will determine the locations and extent of bomb damage. They will also observe the types of damage (caused by various weapons) and make an initial evaluation of the repair effort required.

Block 3.2 - Locate mined areas - In addition to assessing the damage, the RDA crew will also observe and note the locations of mined areas of the runway system. This information will be used in determining the location for the emergency runway; exact location and extent of mined areas for clearing purposes will be determined separately by the mine clearing crew.

Block 3.3 - Record on summary maps - The information obtained by the RDA team will be plotted on the scaled survey map.

d. Establish Runway Centerline and Boundaries (Block 4)

The final task of the RDA team is to determine a location for the emergency runway and to mark its boundaries so that repair activities can begin.

Block 4.1 - Is the area mined? - Mined areas offer a significant barrier to rapid repair activities. Normally, more than an hour is required to clear the mines before repair work can begin, and even then there is the danger of overlooked or unexploded mines. Therefore, the presence of mines will have a significant impact on the area chosen for RRR activities.

Block 4.2 - Is there a runway area clear of mines? - Efforts should be made to locate an area of sufficient size (50 feet x 5000 feet) which is clear of mines, considering also the extent of damage and availability of repair materials.

Block 4.3 - Select unmined runway area - An unmined area should be selected for the emergency runway if available, providing that repair efforts in this area would not require more time than both mine clearing and repair of other sites.

Block 4.4 - Select least damaged runway area - If both the primary and secondary runways have been mined, the least damaged area (the area which can be most quickly repaired) should be selected. The concentration of mines has little effect on clearing operations as the entire area must be swept whether heavily or lightly mined.

Block 4.5 - Use existing centerline? - Can the emergency runway be located on a portion of the runway using the existing centerline?

Block 4.6 - Which runway is most heavily damaged? - This decision point would be considered if the runway area was not mined.

Block 4.7 - Select secondary runway.

Block 4.8 - Select primary runway - The least damaged runway or runway area would be selected.

Block 4.9 - Use existing centerline? - Can the emergency runway be located on a portion of the runway using the existing centerline?

Block 4.10 - Select new centerline - Using the survey map showing the location and extent of damage and the location of mined areas, the runway template would be used to determine where the emergency runway would be located to minimize repair activities. The selected location could be on, parallel to, or at an angle to existing runway centerlines.

Block 4.11 - Mark runway centerline - Once the emergency runway location has been determined, the centerline will be marked using the dye markers included in the RDA equipment list. The coordinates of the centerline should also be communicated by radio to the mine clearing, EOD, and repair crews.

Block 4.12 - Mark runway boundaries - The final task of the RDA team is to place dye markers along the boundaries of the emergency runway to assist ground crews in limiting their activities to the most critical area.

2. Crater Dimensions

As the study of the repair of runways was initiated, it became apparent that little information existed in the literature on hand as to crater diameter, upheaval zone, and debris distribution for standard craters as a function of explosive weight. Accordingly, these trends had to be developed or estimated.

Reference 1 was searched for apparent crater diameter/depth of burial/charge weight information from 193 craters. These data were organized according to the relationship developed by Westine (see Reference 2) and plotted. The data is shown in Figure 6, as well as the general trend lines extracted from Westine's work for craters in alluvium. From this figure, it is evident that there exists no strong trend of soil type or concrete surface thickness. The equations illustrated in the figure are to be considered approximations that need to be defined more closely for specific applications. The symbols used in this and subsequent figures are as follows:

W = Explosive Weight (equivalent TNT), Lb.

R = Apparent Crater Radius, Ft.

d = Depth of Charge Burial, Ft.

Next, Reference 1 was examined for data on the maximum crater radius as a function of the charge weight (in equivalent pounds of TNT) This relationship is illustrated in Figure 7.

General trends of upheaval and debris distribution are needed to establish equipment requirements and work patterns. Again, since little empirical or theoretical data was available, estimates had to be made. Figure 8 illustrates these estimates. The apparent crater maximum radius was taken from Figure 7 where:

$$R\ max\ (AC) = 3.381\ W^{7/24} \qquad (1)$$

R max (AC) = Maximum Apparent Crater Radius, Ft.

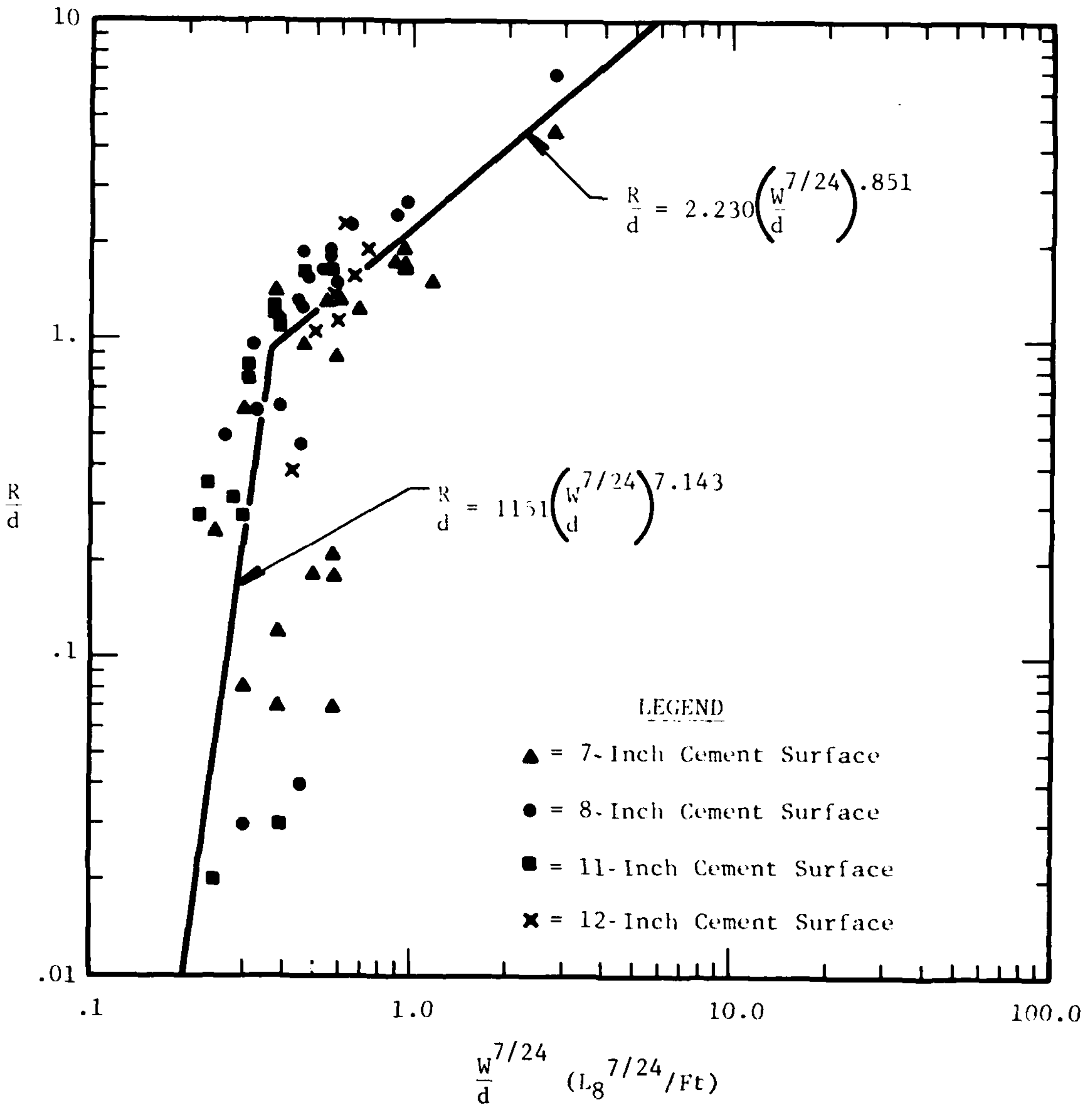


Figure 6. Crater Radius Versus Charge Weight and Depth of Burial

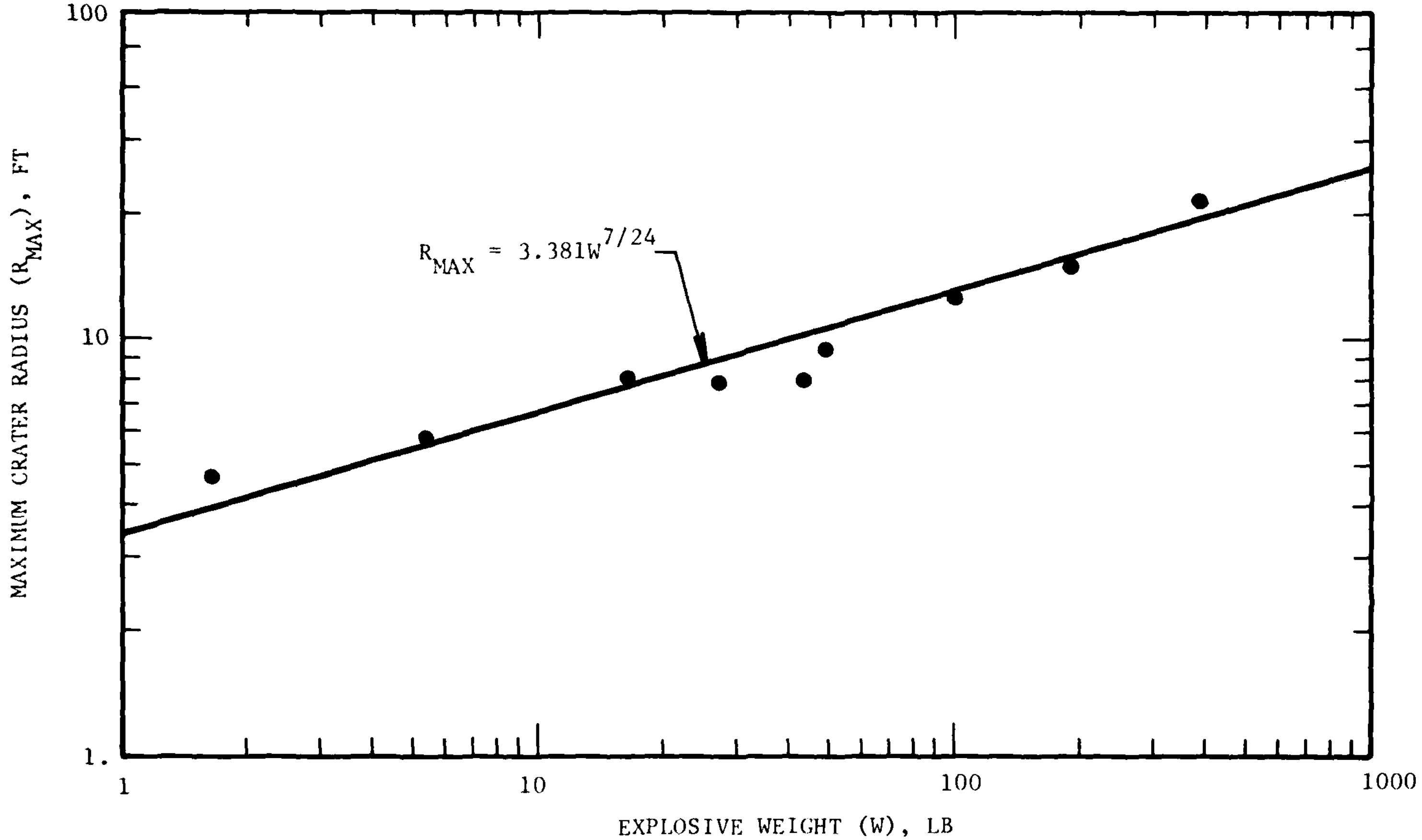


Figure 7. Maximum Crater Radius Versus Charge Weight

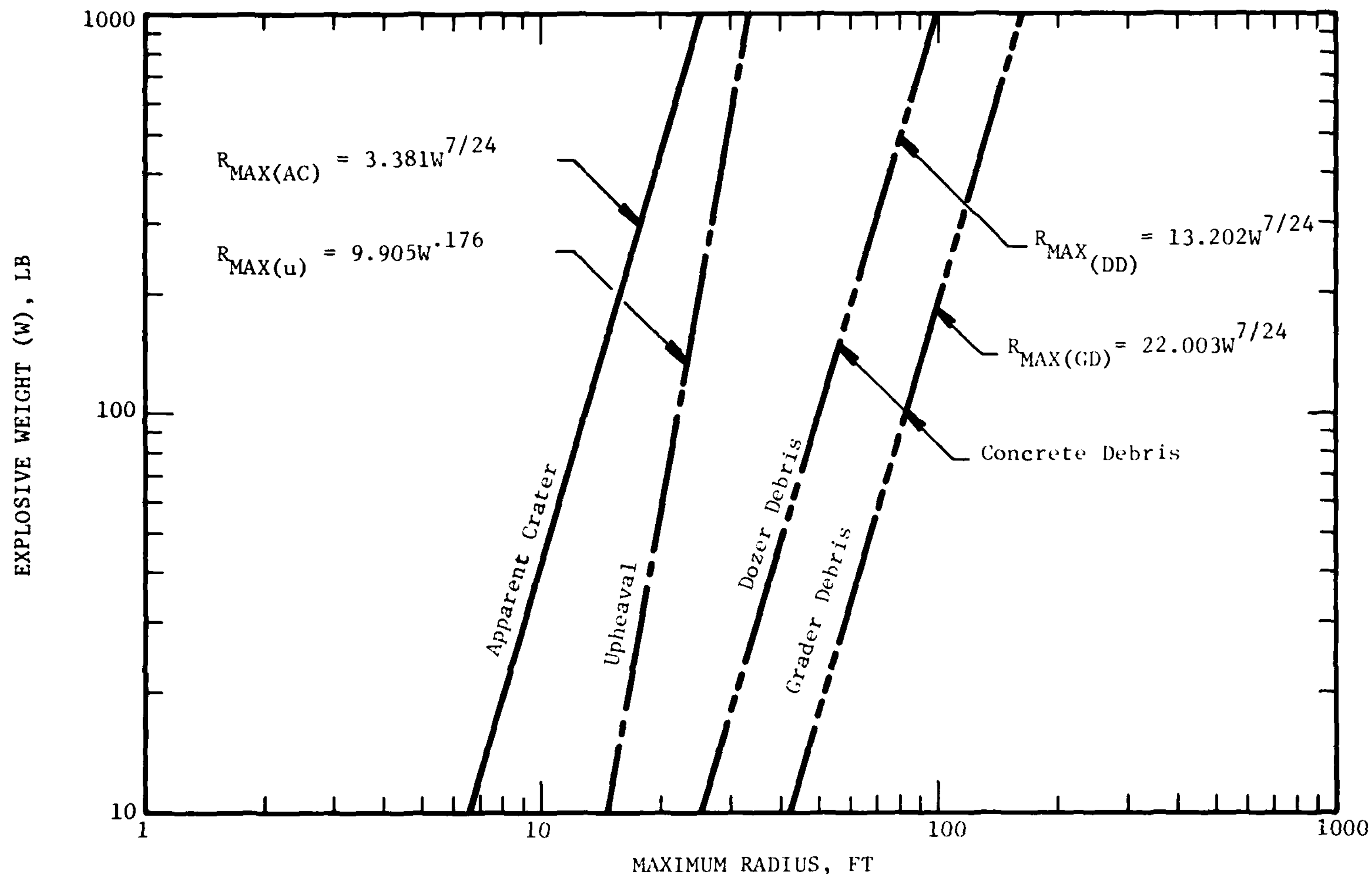


Figure 8. Maximum Radius Versus Explosive Weight

The maximum upheaval radius was extracted from information from Reference 1 by considering the surface area to be the upheaval area (that relation appeared to correlate with test results). The upheaval radius is then:

$$Ru = \frac{Au}{\pi} + R^2_{AC}{}^{1/2} \qquad (2)$$

Where: Ru = Upheaval Radius, Ft

Au = Surface Area, Ft^2

R_{AC} = Apparent Crater Radius, Ft

Using the data from Reference 1, the following relations were estimated:

$$R\ max\ (u) = 9.905\ W^{.176} \qquad (3)$$

Where: R max (u) - Maximum Upheaval Radius, Ft.

There is a dearth of information on the distribution of debris about a crater. To arrive at an estimate, two assumptions were made: (1) Dozer type equipment would be needed within a 75-foot radius of a 750-pound bomb crater (maximum size), and that grader-type equipment can be used beyond this radius out to a maximum radius of about 125 feet. These estimates were based on the debris distribution shown in Reference 3. (2) The debris radius/charge weight relation scales by $W^{7/24}$.

Based on these assumptions the following relations were estimated:

$$R\ max\ (DD) = 13.202\ W^{7/24} \qquad (4)$$

Where: R max (DD) = Radius inside of which dozer type of equipment will be needed, ft

$$R\ max\ (GD) = 22.003\ W\ 7/24 \qquad (5)$$

Where: R max (GD) = Radius inside of which grader type of equipment can be used (up to R max (DD)), ft

The debris distribution given in Figure 8 relates primarily to the concrete ejecta distribution. A careful review of reports on the repair of several craters (References 4 and 5) indicated that the ejecta distribution had a significantly smaller radius than that considered in Reference 3. Consequently, Reference 6 was reviewed in detail since that report has specific information on many craters.

As a result of this review, it was concluded that the debris distribution of Reference 3 is probably acceptable for the consideration of the concrete debris. However, the soil debris will have a significantly different distribution. A close examination of Reference 6 indicated that the prediction of the maximum ejecta volume indicated by Figure 52 of that reference differs significantly from test data found in Volume II of that report. This difference is shown in Figure 9. Figure 9 is a plot of maximum ejecta volume

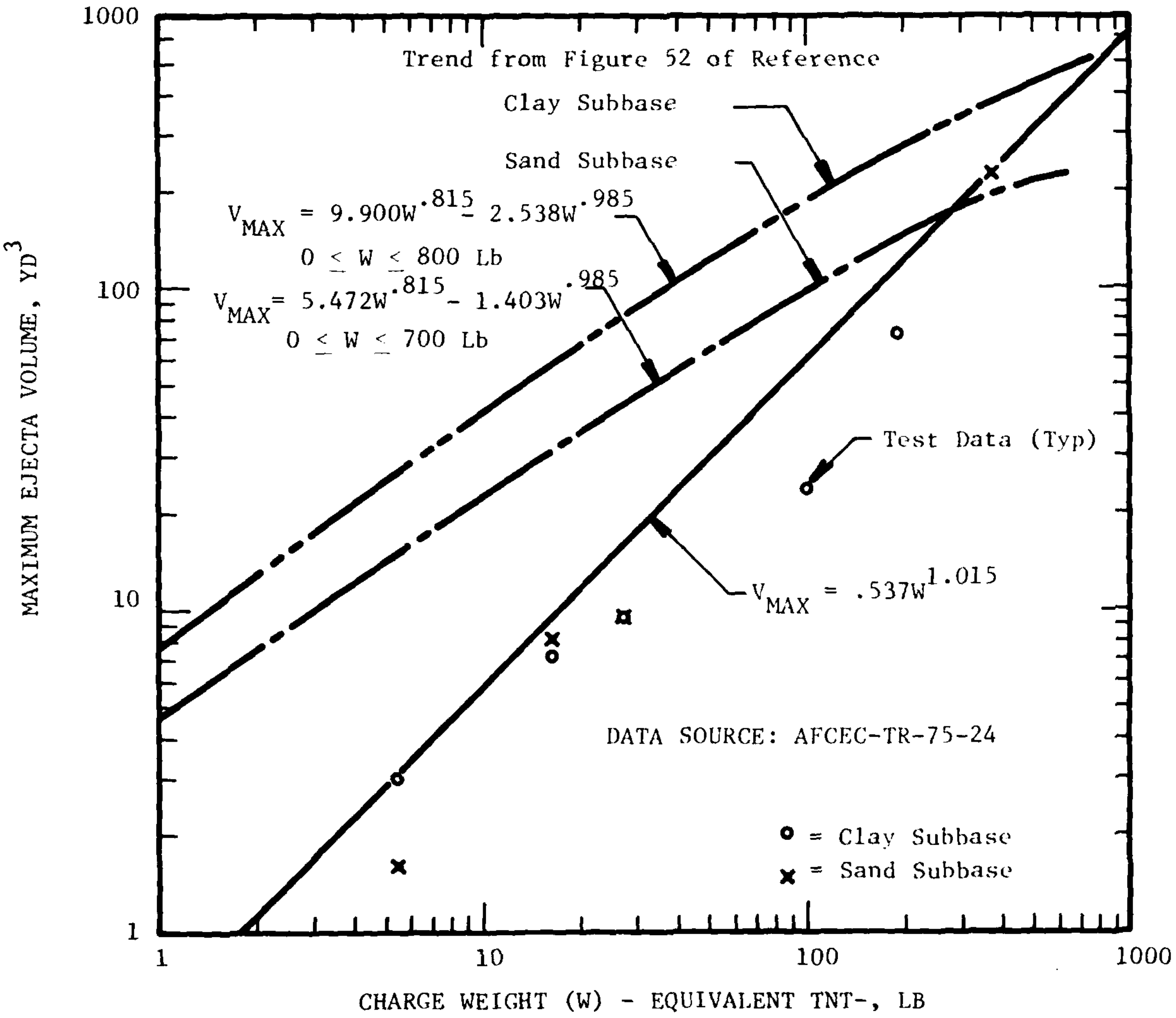


Figure 9. Maximum Ejecta Volume Versus Charge Weight

as a function of charge weight. Three curves are illustrated in the figure: The upper curve relates to the trend predicted by Figure 52 of Reference 6 for craters in clay subbase; the middle curve relates the trend in Figure 52 (Reference 6) for sand subbase; and the lower curve is a prediction based on the test data given in Volume II of the referenced document. Data points are illustrated for sand and clay subbase. The trend line illustrated by the heavy line appears to be in closer agreement to the test data for the lower charge weights. This trend line has the form:

$$V_{max} = .537\ W^{1.015} \tag{6}$$

Where: V_{max} = Maximum Ejecta Volume, Yd^3

W = Explosive Weight (equivalent TNT), Lb

Reference 5 has debris distribution data for 750-lb bombs (386 lb of TNT) and 25-lb explosive charges. Figure 10 shows the ejecta distribution for a 750-lb bomb. The upper portion of the figure is a profile of the actual debris distribution. In order to simplify the equipment analysis, this distribution was replaced by the rectangular distribution illustrated in the lower graph. The table in the lower portion of the figure shows the comparison of the volumes for the three zones illustrated. The approximate distribution is within 8 percent of the actual distribution.

The debris distribution for the 25-lb explosive charges is illustrated in Figure 11. A two-step approximation is adequate for the smaller charges.

3. Equipment

Equipment one-on-one models have been placed into a category of activity because they are used in several operations, e.g., repair of alternate runway and repair of primary runway. Each one-on-one model is defined only to that level which will allow reasonable estimates of production, speed, and time. The models should also allow trades to be made of effectiveness versus equipment size. No detailed definition of equipment models are made since those models require a very significant level of effort.

Reference 7 is the primary data document used for the generation of the models. Although the reference has company peculiar data, it is considered a valuable source document and provides trend data which is reasonably characteristic of the state-of-the-art of construction equipment.

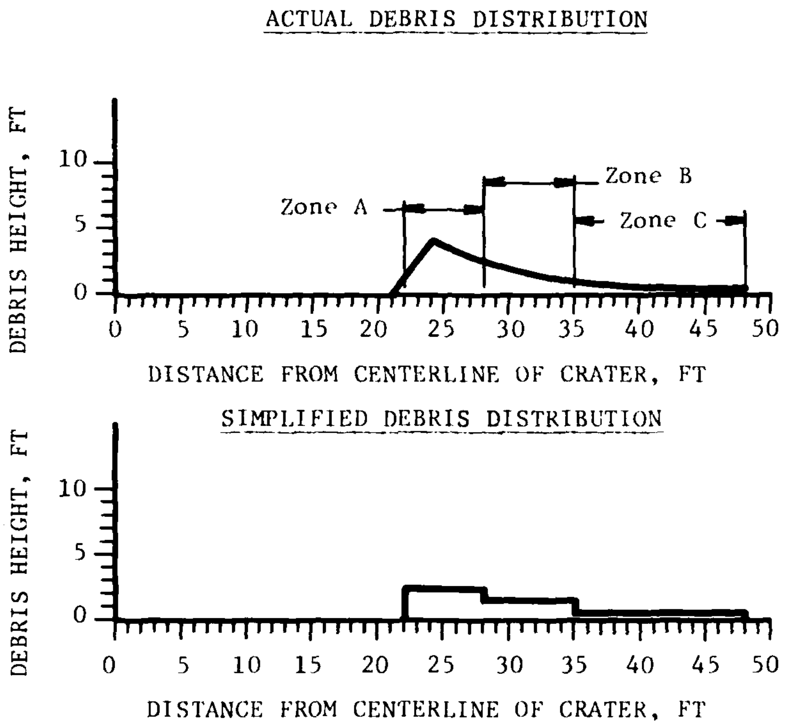
a. Dozer, Tracked

The dozer model should relate speed and volume of material moved to machine characteristics such as weight and power. Figure 12 illustrates the relationship between the power factor

$$\left(\frac{P}{wu}\right)$$

and the drawbar pull

$$\left(\frac{P}{w}\right)$$

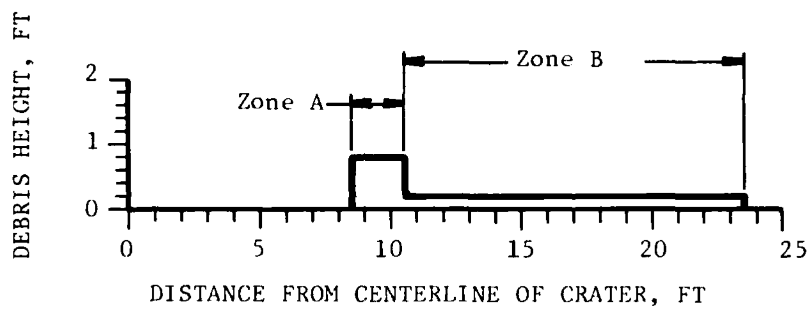


VOLUMETRIC DISTRIBUTION COMPARISON

	Actual Volume Yd^3	Approximate Volume Yd^3	Depth Ft
Zone A	105	100	2.5
Zone B	72	77	1.5
Zone C	45	62	0.5

Source: AFWL-TR-74-226

Figure 10. Ejecta Distribution for 750-Lb Bomb



VOLUMETRIC DISTRIBUTION

	Approximate Volume Yd^3	Approximate Depth Ft
Zone A	3.5	0.8
Zone B	15.0	0.2
Total	18.3	

SOURCES: AFWL-TR-74-226
And Figure 1

Figure 11. Ejecta Distribution for 25-Lb Bomb

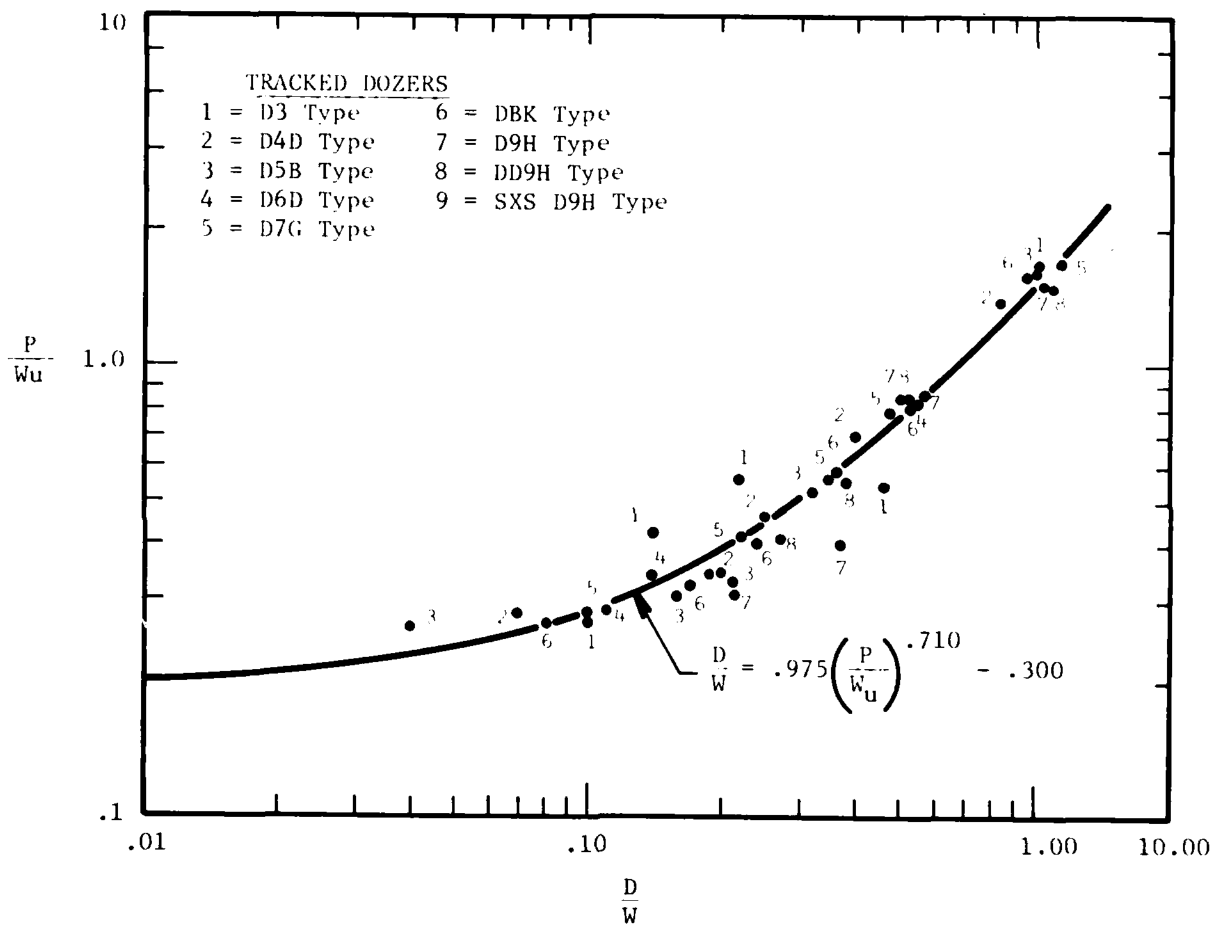


Figure 12. Drawbar Pull Versus Power Factor

for various tracked dozers. The curve represents the approximate relationship and is expressed by:

$$\frac{D}{W} = .975 \left(\frac{P}{WU}\right)^{.710} - .300 \quad (7)$$

Where: D = Drawbar Pull, Lb

W = Vehicle Weight, Lb

P = Vehicle Power, Ft-Lb/Sec

U = Vehicle Speed, Ft/Sec

Equation (7) can be rearranged to yield the speed explicitly.

$$U = .965 \frac{P}{W}\left(\frac{W}{D + .3W}\right)^{1.408} \quad (8)$$

The maximum drawbar pull that the dozer can exert can be expressed in terms of either the dozer weight or the power. These relationships are shown in Figure 13 where the maximum drawbar pull is taken at a minimum vehicle speed of 1 mph. The drawbar pull, power relation appears to have somewhat less scatter than the drawbar pull, weight relation. The maximum drawbar pull, then, can be expressed as:

$$D_{max} = .2948 \left(\frac{P}{U_o}\right)^{1.031} \quad (9)$$

The resistance to motion is supplied by the material. This resistance takes the form:

$$R = D = \mu_o \rho V_o \quad (10)$$

Where: μ_o = Overall Drag Factor, dimensionless

($\mu_o \simeq 1.22$)

ρ = Material Density, Lb/Ft^3

V_o = Material Volume, Ft^3

When $R = D_{max}$ the dozer is slowed to 1 mph and, for our purposes, must relieve the load. Equation (10) can be substituted into Equation (8) to yield the vehicle velocity as a function of the volume of material being moved. This relationship is:

$$U = .965 \frac{P}{W}\left(\frac{W}{\mu_o \rho V_o + .3W}\right)^{1.408} \quad (11)$$

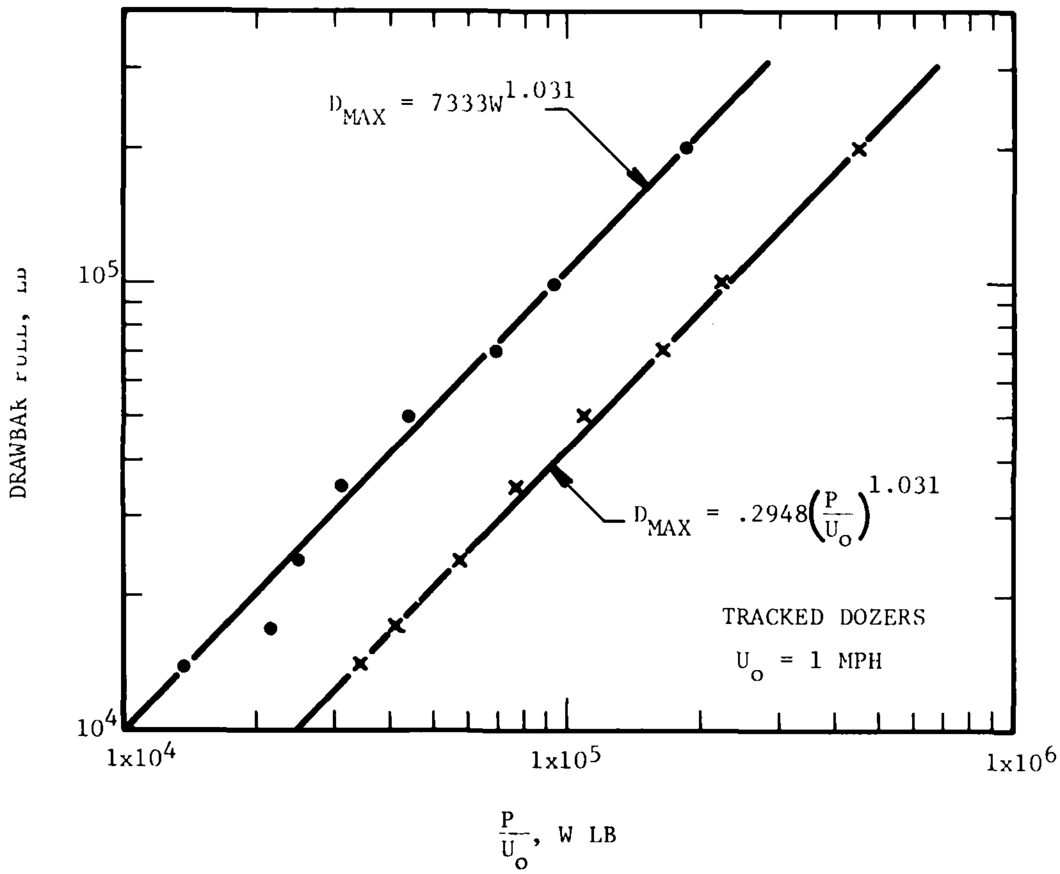


Figure 13. Maximum Drawbar Pull Versus Vehicle Weight or Vehicle Power

Equations (9) and (11) then provide the basis for estimating the production of tracked dozers and determining when the dozer has been filled to its capacity.

b. Dozers, Rubber Tired

The relationship of speed versus dozer characteristics for rubber-tired dozers is similar to that of tracked dozers except rimpull is substituted for drawbar pull and rubber-tired dozers cannot generate the speed of tracked dozers for equal loads, weight, and power.

Figure 14 illustrates the rimpull, power factor relation for wheeled dozers. The rimpull equation is:

$$\frac{D}{W} = .710 \left(\frac{P}{WU}\right)^{.760} - .073 \qquad (12)$$

Solving for the velocity, the equation is of the form:

$$U = .539 \frac{P}{W} \left(\frac{W}{D + .073W}\right)^{1.316} \qquad (13)$$

The maximum rimpull versus weight or power relation of the wheeled dozer closely approximates that of the tracked dozer. Equation (9), then, applied both to the rubber-tired or tracked dozers.

Similarly, Equation (10) applies to any dozer.

The equation of motion for rubber-tired dozers, then, is obtained by combining Equations (10) and (13). This yields:

$$U = .539 \frac{P}{W} \left(\frac{W}{\mu o \rho V o + .3W}\right)^{1.316} \qquad (14)$$

Dozer blade lengths are generally sized to the dozer. This allows a length-weight relationship to be determined. Figure 15 illustrates the data and the curve fit for blade length versus dozer weight for both tracked and rubber-tired dozers. The equation of the curve is of the form:

$$L_B = .1811 \ \mathrm{TAN}^{-1} \ (.0000505 \ W) \qquad (15)$$

Where: L_B = length of blade, ft

W = dozer weight, lb.

It is important to recognize that the relation developed is general. If the blade length for a particular dozer is known, it should be used. The purpose of the relationship is to show the increase in weight required to achieve an increase in blade length.

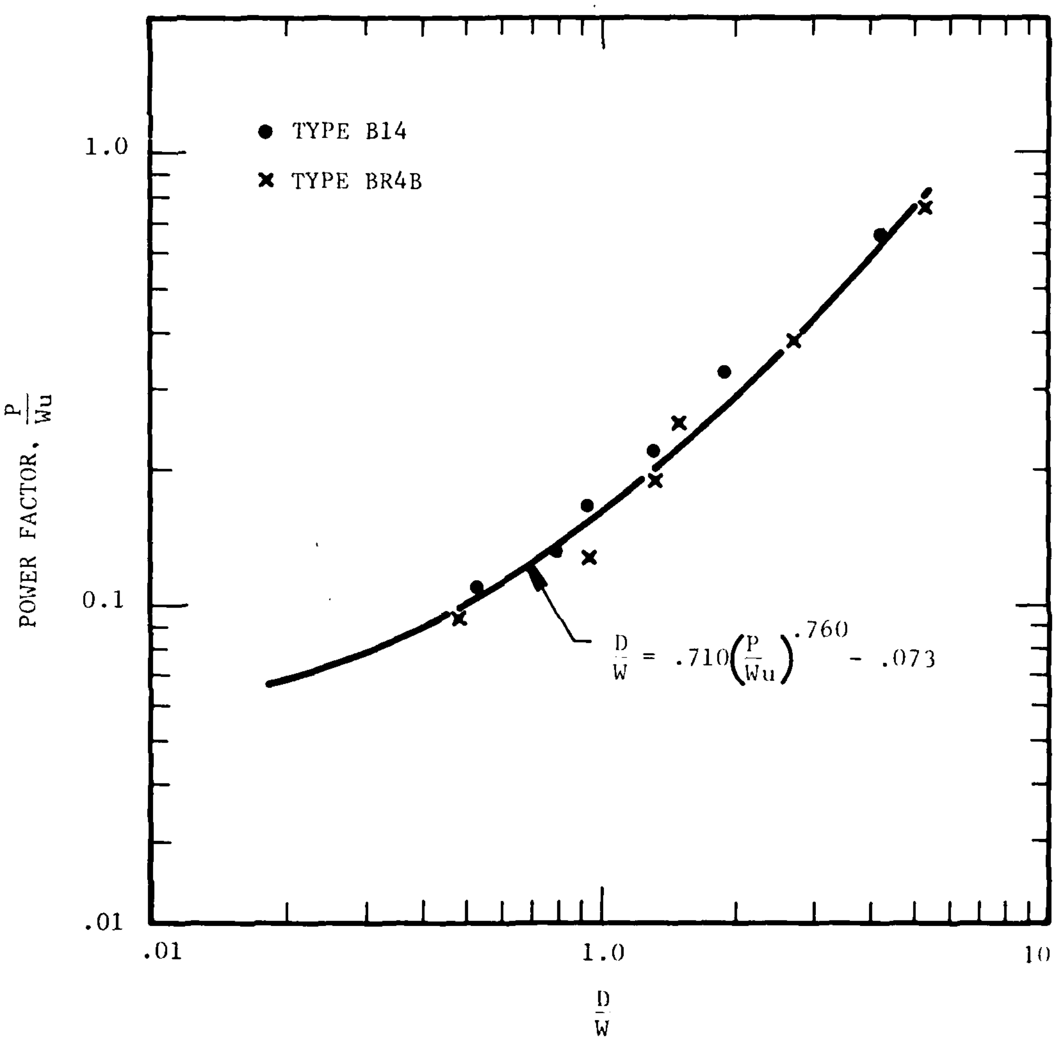


Figure 14. Rimpull Versus Power Factor

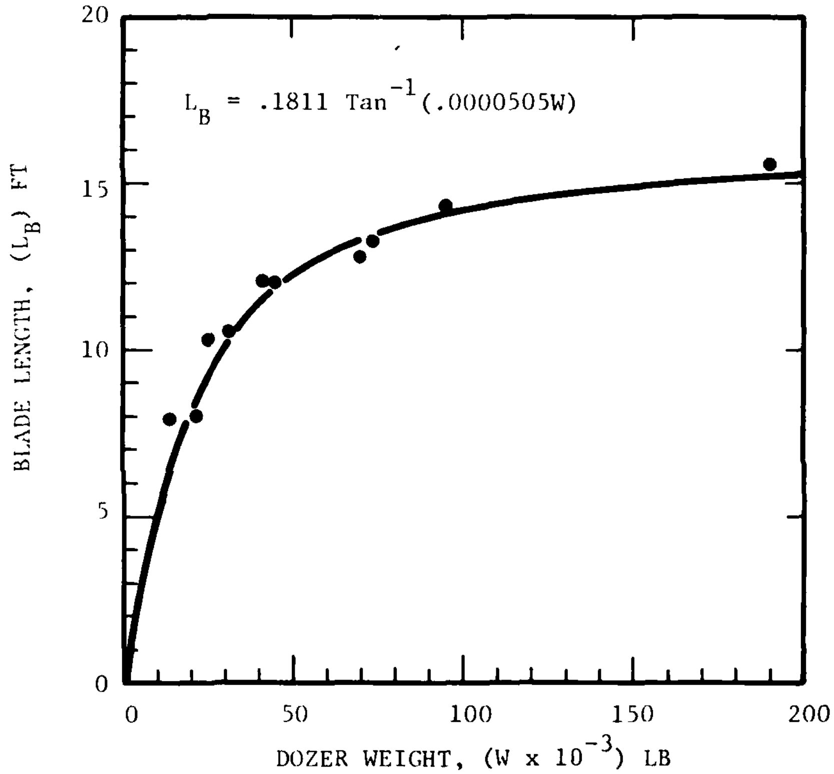


Figure 15. Dozer Blade Length Versus Dozer Weight

c. Wheeled Loaders

The average velocity of wheeled loaders, for travel data to 700 feet, can be estimated by:

$$\bar{U}_u = 1.615 \frac{p}{\rho_f V_f} \tag{16}$$

and

$$\bar{U}_L = 1.909 \left(\frac{Wu}{W_u + \rho V_f}\right)\left(\frac{p}{\rho_f V_f}\right) \tag{17}$$

Where: $\bar{U}_u$ = Average speed of loader, unloaded, fps

$\bar{U}_L$ = Average speed of loader, loaded, fps

W_u = Operating weight of loader, unloaded, fps

V_f = Volume of bucket, struck, with 90% fill factor, Yd^3

ρ_f = Density of fill, Lb/Yd^3

If the fill volume is not available, it can be estimated by the use of Figure 16 or the equation:

$$V_f = .300\, W_u^{.320} - 5.50 \tag{18}$$

d. Graders or Wheeled Dozers With Angled Blades

The equation of motion for graders is derived from the equation of motion for wheeled dozers. It is postulated that the drag or resistance force will be of the form:

$$R = R_o \sin\theta \tag{19}$$

Where: R = Drag force, Lb

R_o = Drag force with blade set at 90°, Lb

θ = Blade angle (angle between blade and centerline of grader), degrees

Equation (13) can be rewritten in the form:

$$U = .539 \frac{P}{W}\left(\frac{W}{D \sin\theta + .073W}\right)^{1.316} \tag{20}$$

Since $D = R = \mu o \rho V o$ (Equation (10))

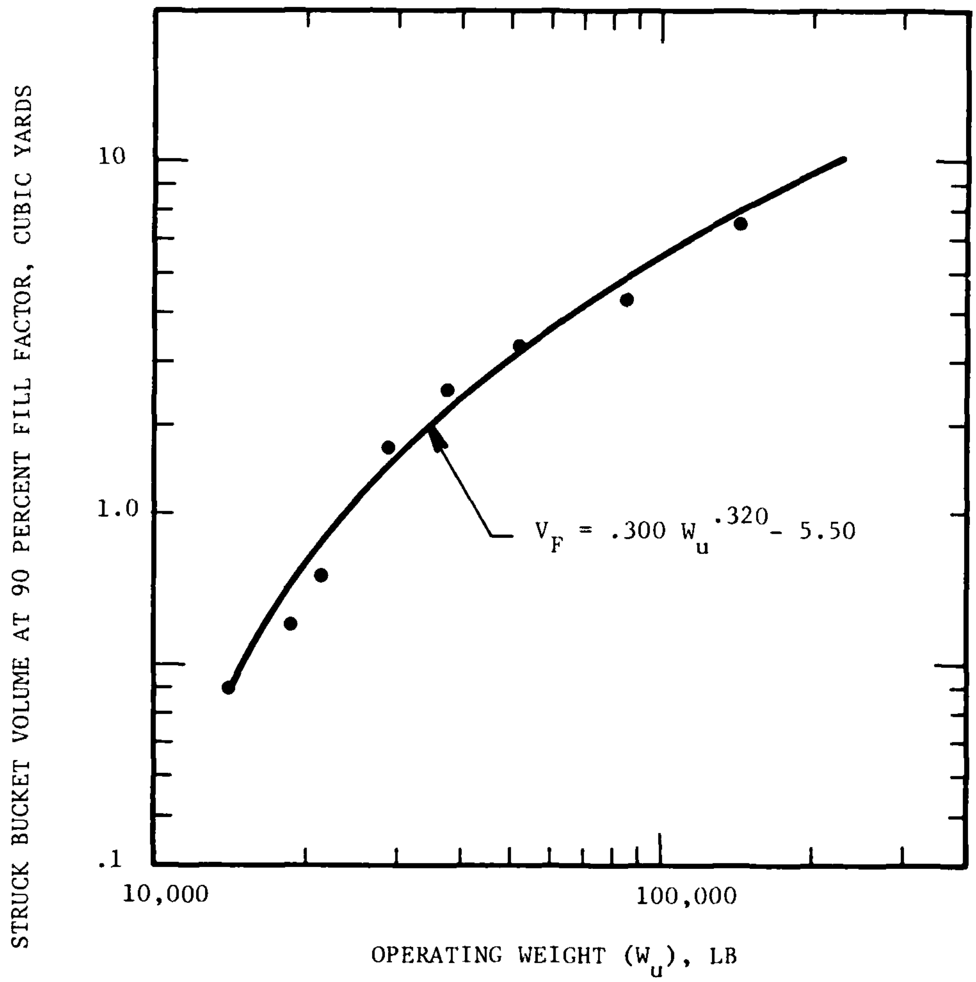


Figure 16. Bucket Volume Versus Vehicle Weight

$$U = .539\,\frac{P}{W}\left(\frac{W}{\mu o \rho V o\ \sin\theta + .073W}\right)^{1.316} \qquad (21)$$

The maximum rimpull can be obtained from Equation (9).

e. Excavators

The primary purpose of the excavator in RRR role is to remove large chunks of concrete. The lifting capacity of the excavator and its cycle time are important characteristics relative to this role. Excavators can lift concrete chunks either as a side or a front lift. As would be expected, the front lift capability is somewhat greater than that of the side lift.

The lifting capacity is dependent on the weight of the excavator, the reach needed to engage the load, and a characteristic dimension such as the width or the length of track contact. Further, the maximum lift is determined by the excavator's tipping potential. However, at short radii the lifting capacity may be determined by the power limits of the excavator.

Cycle time is made up of four elements: (1) load, (2) swing loaded, (3) dump, and (4) swing unloaded. This time is dependent on the power of the excavator, its mass, and its mass distribution.

As with most of the previous equipment models, Reference 7 has been used to characterize the excavator generally. There are wide ranges of excavator properties so that the models presented are to be used as gross indicators of typical excavators. In a detailed analysis of particular equipment, certainly the equipment characteristics should be used.

The characteristics of four excavators were examined and modeled. These characteristics are compiled in Table 2. Figure 17 illustrates the side lift capability as a function of the lift radius and Figure 18 illustrates this relationship for the front lift. The curves show the relationship represented by the equations:

$$L_s = \frac{.045\ W\ C^{2.5}}{R^{1.5}} \qquad (22)$$

and

$$L_f = .116\ W\ \frac{H}{R}^{1.25} \qquad (23)$$

Where: L_s = Side lift capacity, lb

L_f = Front lift capacity, lb

W = Total excavator weight (without fill weight), lb

C = Track width of excavator, ft

H = Track contact length of excavator, ft

R = Lift radius, ft

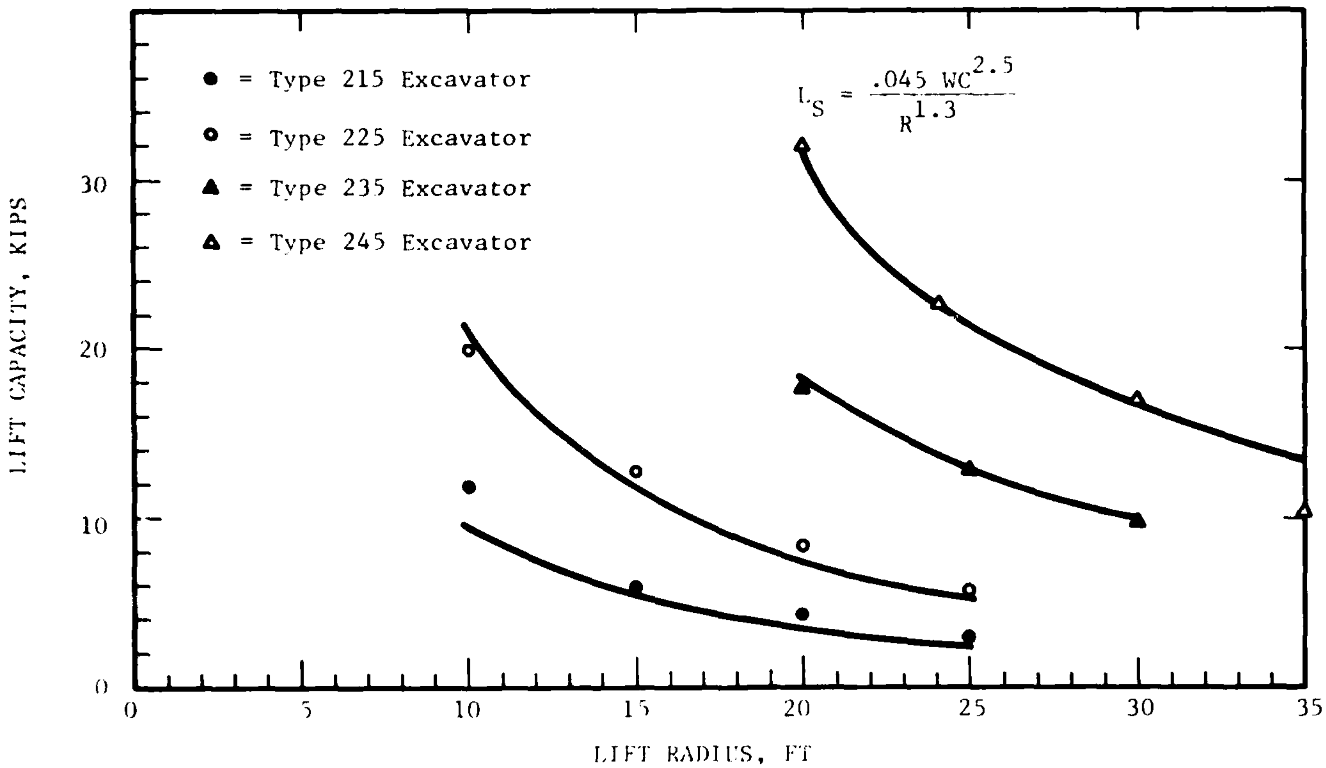


Figure 17. Side Lift Capacity Versus Lift Radius

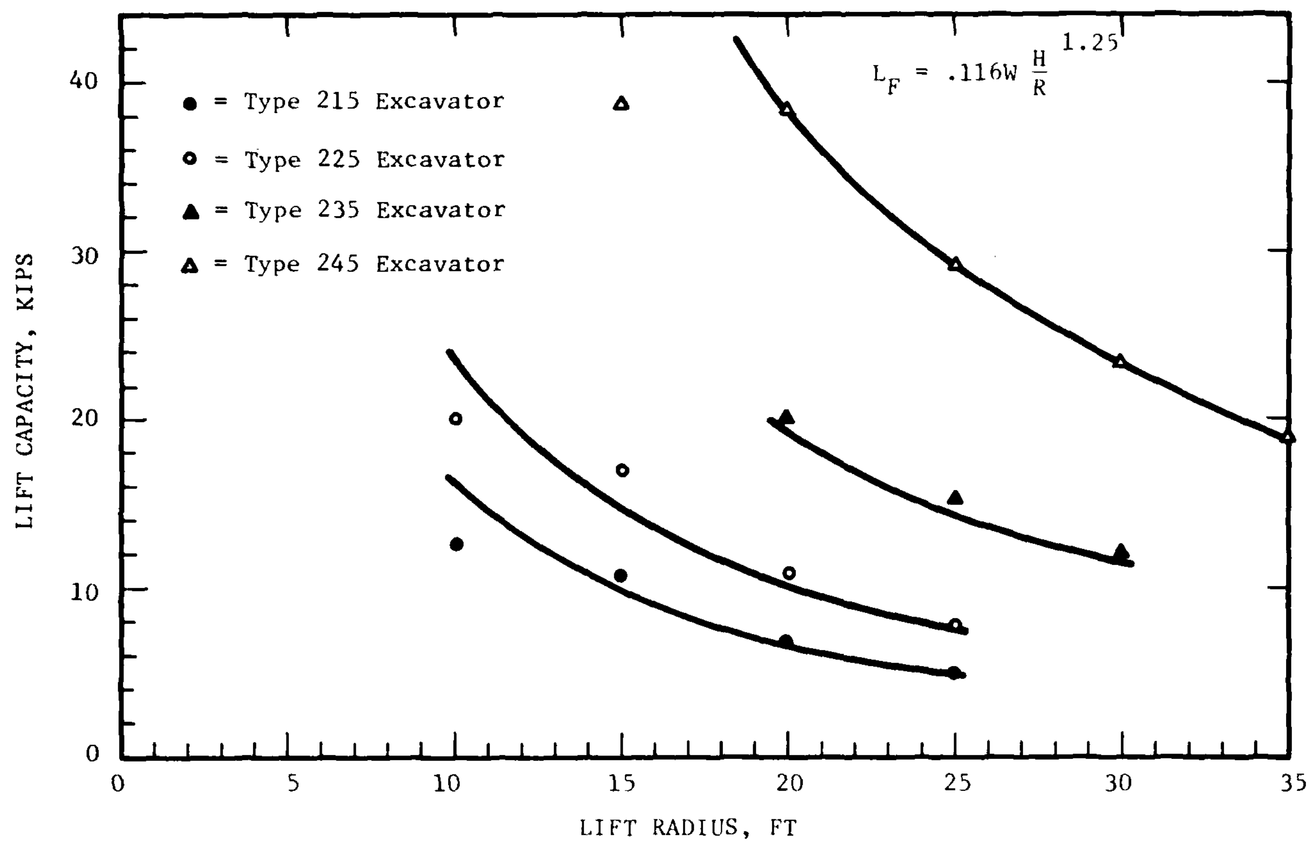


Figure 18. Front Lift Capacity Versus Lift Radius

TABLE 2. EXCAVATOR CHARACTERISTICS

Model No.	Total Weight (Lb)	Flywheel Power (HP/Ft-Lb/Sec)	Struck Bucket Capacity (Yd³)	Cycle Time (Sec)		
				Load and Dump	Total Swing	Total Cycle
215	37,510	85 / 46,750	1.0	22.0	8.0	30
225	48,332	125 / 68,750	1.2	27.0	9.0	36
235	75,955	195 / 107,250	1.9	31.0	11.0	42
245	126,475	325 / 178,750	2.6	37.0	13.0	50

As indicated by Figures 17 and 18 the curves provide a reasonable fit for the larger excavators and for the large lift radii. The curve fit was based on a tipping limit and at the shorter radii the hydraulic power capacity limits the lift.

The cycle time relation is indicated in Figure 19. The weight/power factor relates reasonably well to the cycle time. It was expected that the load and dump time would have a different relation form than the swing time. However, one form appears to offer a reasonable fit. The lighter machine (Type 215) appears to deviate from the curve somewhat. The time relations are:

$$\tau_T = 1.265 \left(\frac{W}{p^{.5}}\right)^{.827} \qquad (24)$$

$$\tau_s = .331 \left(\frac{W}{p^{.5}}\right)^{.827} \qquad (25)$$

$$\tau_{LD} = .934 \left(\frac{W}{p^{.5}}\right)^{.827} \qquad (26)$$

Where: τ_T = Total cycle time, sec

τ_s = Total swing time, sec

τ_{LD} = Load and dump time, sec

p = Excavator flywheel power, ft-lb/sec.

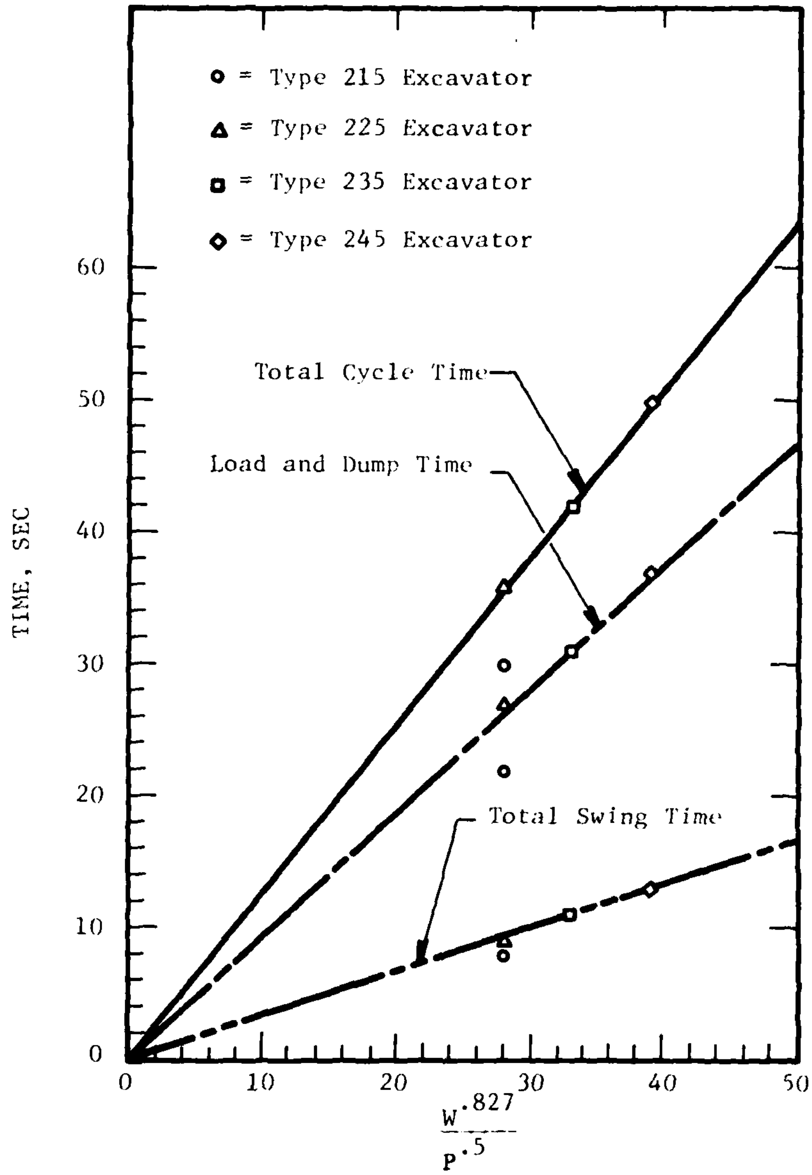


Figure 19. Time Versus Weight/Power Factor

The maximum capacity bucket was chosen for each excavator primarily because it is also the widest bucket. Maximum width is needed to minimize the need to break concrete slabs into smaller pieces. Bucket capacity relates to the total excavator weight according to the relationship illustrated in Figure 20. Struck bucket capacity is used to reflect an ability to excavate which is closer to actual conditions than if the heaped bucket capacity were used.

$$C_s = .00028\ W^{.779} \tag{27}$$

Where: C_s = Struck bucket capacity, Yd^3.

Bucket width is also of interest. This relation, however, is not as neat as that of the capacity. For the buckets identified, the maximum bucket widths are 54 inches for Type 215 and 225 excavators and 60 inches for Type 235 and 245 excavators.

f. Compactors

A review of the literature and the prominent texts on soil membranes and the process of compaction did not reveal an accurate, predictive compaction model. In addition, the data at hand was insufficient to structure such a model. As a remedy for this problem, a separate study of soil compaction was undertaken as part of this project.

The compaction model which is found in Appendix B relates the strength of the soil to the soil characteristics, to the compactor characteristics, and to the number of coverages. The measure of merit for soil strength chosen for that study is the California Bearing Ratio (CBR).

In addition to the analytical study of soil compaction which developed the compactor model, the effectiveness of three types of compactors was studied. The vibrating compactor appears to give a consistently higher compaction density factor than the rubber-tired roller. In addition, experimental results indicate that the sheepsfoot roller produces higher density factors than either the vibrating or the rubber-tired roller for lean clay and clayey sand. The complete explanation of the experimental data on compactors is found in the literature contained in Appendix B.

4. Materials

The study of materials applicable to repair of bomb damaged runways was divided into two topics. The first material requirement is for fill of the crater up to approximately 6 inches of finished grade. The second material requirement is for a cap for the fill to provide at grade a surface with enough strength to support the aircraft.

a. Material Descriptions

The specific description of repair materials and their respective characteristics are found in Appendix C.

b. Material Evaluation

A number of material combinations were subjectively evaluated for possible use in the RRR program as either a fill or cap material. The

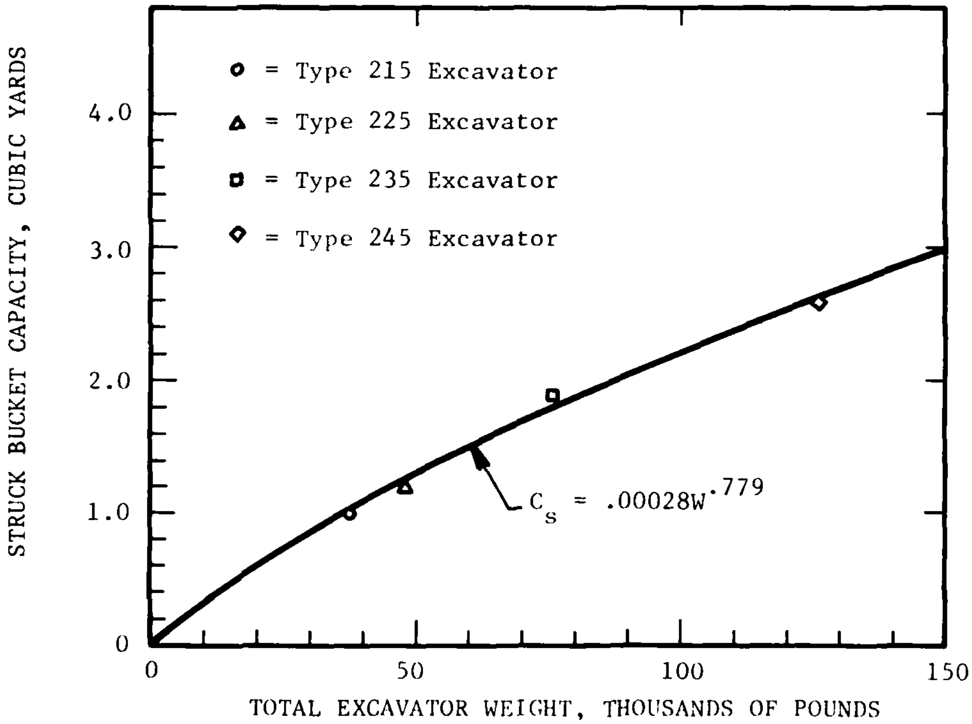


Figure 20. Struck Bucket Capacity Versus Excavator Weight

evaluations were based on firsthand knowledge and experience of one or more of the contractor project team or on the results of discussions with technical personnel who did have experience with a given material for similar applications. The criteria used to evaluate the materials combinations were the following:

- Strength
- Set time
- Environmental effects on the product
- Shelf life and the required resupply
- Mixing and dispersing equipment required
- Adhesive properties
- Safety
- Cost

The results of these evaluations were tabulated in a matrix form and are presented in Tables 3 and 4. An evaluation of O - outstanding, A - acceptable, M - marginal or U - unacceptable was assigned to each material combination that was considered for use as either a fill or cap material. A blank was indicated for combinations that were not applicable for a given application. These evaluations were made independent of any specific repair technique and were considered only in general terms during this evaluation.

C. Preliminary Concepts

The concepts presented in this section of the report for the rapid repair of a main runway and the repair and/or construction of an alternate strip are preliminary in nature. Sufficient information has been developed about each concept to determine whether to conduct a detailed investigation of each of the proposed systems during the next phase of the project. Since the construction and repair techniques associated with the main and alternate strips may be significantly different from each other, the repair concepts for each type of runway are presented in separate subsections.

1. Preliminary Concepts for Repair of Main Runways

There have been a number of different concepts that have been proposed as methods of repairing bomb damaged runways. For the most part, the concepts proposed prior to this contract have concentrated on repairing the runway within a 4- to 8- hour period. As stated earlier, the concepts considered on this program were designed to approach a repair time of one hour. The concepts presented in this section of the report could be deployed and have the possibility of offering a repair time of approximately one hour with the proper materials, equipment, and trained personnel.

Each of the concepts will be presented in the same format for ease of presentation and clarity. A brief description of the concept will be presented

TABLE 3. FILL MATERIAL EVALUATION

	ALONE	SAND	AGGREGATE	SOIL	FIBERGLASS	EXPANDED STYRENE	UNEXPANDED STYRENE	PLASTIC SPHERES	INORGANIC SPHERES	FOAMING AGENT	CEMENT	GYPSUM CEMENT	PLASTER	FLY ASH	ASPHALT	CRUSHED DEBRIS	FREEZE	GELL
ALONE		A	A+	M	–	U	U	M	M	–	M	M	M	M	U	A	–	–
DEBRIS	M	A	A	M	–	U	–	M	M	–	A	A	A	A	M	A	–	–
CRUSHED DEBRIS	A	A	A	A	–	U	U	M	M	–	A	A	A	A	M	–	–	–
SAND	A	–	A+	A	–	U	–	M	A	–	A	A	A	A	M	A	–	–
AGGREGATE	A+	A+	–	A	–	U	–	M	M	–	A+	A+	A	A	M	A	–	–
EPOXY	U	M	M	U	M	M	M	M	A	M	M	M	M	M	M	M	–	–
POLYESTER	U	A	A	U	A	U	U	M	A	A	M	M	M	M	U	M	–	–
WATER EXT POLYESTER	U	A	A	M	A	U	U	M	A	M	A	A	A	A	U	A	–	–
METHYL METHACRYLATE	U	M	M	U	A	U	U	M	A	M	M	M	M	M	U	M	–	–
URETHANE	U	M	A	U	A	U	U	M	A	A	M	M	M	M	U	M	–	–
POLYURETHANE FOAM	A	U	U	U	M	U	U	M	M	–	U	U	U	U	U	U	–	–
AMINOS	U	M	A	M	A	M	M	M	A	M	A	A	A	A	U	A	–	–
PHENOLICS	U	M	M	U	M	U	U	M	A	M	M	M	M	M	U	M	–	–
FURANS	U	A	A	U	A	U	U	M	A	M	M	M	M	M	M	M	–	–
ALLYLS	U	M	M	U	M	U	U	M	M	M	M	M	M	M	U	M	–	–
ALKYDS	U	M	M	U	M	U	U	M	M	M	M	M	M	M	U	M	–	–
SILICONE	U	U	M	U	M	M	M	M	M	M	M	M	M	M	U	M	–	–
CEMENT	M	A	A+	A	M	A	M	M	A+	A	–	A	A	A	U	A	–	–
GYPSUM CEMENT	U	M	A+	M	M	M	U	M	A+	M	A	–	A	A	M	A	–	–
PLASTER	U	A	A	A	A	A	M	A	A	A	A	A	–	A	M	A	–	–
FLY ASH	M	A	A	A	A	A	M	A	A+	A	A	A	A	–	M	A	–	–
SULFUR	U	M	M	M	U	U	U	U	M	M	M	M	M	M	U	M	–	–
WATER	U	A	U	U	–	U	U	U	U	–	M	M	M	M	U	U	M	M

O – OUTSTANDING   A – ACCEPTABLE   M – MARGINAL   U – UNACCEPTABLE

TABLE 4. CAP MATERIAL EVALUATION

	ALONE	SAND	AGGREGATE	SOIL	FIBERGLASS	EXPANDED STYRENE	UNEXPANDED STYRENE	PLASTIC SPHERES	INORGANIC SPHERES	FOAMING AGENT	CEMENT	GYPSUM CEMENT	PLASTER	FLY ASH	ASPHALT	CRUSHED DEBRIS	FREEZE	GELL
ALONE		M	M	M	–	U	U	M	M	–	A	A	A	A	M	M	–	–
DEBRIS	U	U	U	U	–	U	–	U	U	–	M	M	M	M	M	M	–	–
CRUSHED DEBRIS	M	M	M	M	–	U	–	U	U	–	A	A	A	A	M	M	–	–
SAND	M	–	M	M	–	U	–	M	M	–	A	A	A	A	M	M	–	–
AGGREGATE	M	M	–	M	–	U	–	M	M	–	A	A	A	A	M	M	–	–
EPOXY	A	A	O	M	A	M	M	M	A	M	M	M	M	M	M	M	–	–
POLYESTER	A	O	O	M	A	U	U	M	M	M	M	M	M	M	U	M	–	–
WATER EXT POLYESTER	A	O	O	A	A	U	U	M	M	M	A	A	A	A	U	A	–	–
METHYL METHACRYLATE	A	O	O	M	A	U	U	M	A	M	M	M	M	M	U	M	–	–
URETHANE	A	O	O	M	A	U	U	M	A	M	M	M	M	M	M	M	–	–
POLYURETHANE FOAM	M	M	M	M	M	U	U	M	M	–	U	U	U	U	U	U	–	–
AMINOS	A	A	A	A	A	M	M	M	A	M	A	A	A	A	U	A	–	–
PHENOLICS	A	A	A	M	A	U	U	M	A	M	M	M	M	M	M	M	–	–
FURANS	A	O	O	M	A	U	U	M	A	M	M	M	M	M	U	M	–	–
ALLYLS	M	M	M	M	M	U	U	M	M	M	M	M	M	M	U	M	–	–
ALKYDS	M	M	M	M	M	U	U	M	M	M	M	M	M	M	U	M	–	–
SILICONE	U	U	U	U	U	U	U	M	M	U	M	M	M	M	U	M	–	–
CEMENT	A	O	O	M	A	M	M	M	O	A	–	A	A	A	U	A	–	–
GYPSUM CEMENT	A	O	O	M	A	M	M	M	O	A	A	–	A	A	M	A	–	–
PLASTER	A	O	O	M	A	M	M	M	O	A	A	A	–	A	M	A	–	–
FLY ASH	A	O	O	M	A	M	M	M	O	A	A	A	A	–	M	A	–	–
SULFUR	M	M	M	U	U	U	U	U	U	M	M	M	M	M	U	M	–	–
WATER	–	A	M	U	–	U	U	U	U	U	M	M	M	M	U	U	A	M

O – OUTSTANDING A – ACCEPTABLE M – MARGINAL U – UNACCEPTABLE first with a sketch of the concept. Then the following information about each concept will be presented in tabular form:

- Materials - The primary materials suggested for the cap and fill with the concept will be presented first.

- Weight of material required to fill a volume of 150 yd^3 - This volume, which is approximately equal to the additional volume of material required to fill a crater formed by a 750-pound bomb, is presented for comparison between concepts.

- Costs - The relative cost of materials and special equipment will be presented for each concept. A low cost indicates <\$1 million/repair. A medium cost indicates between \$1 and \$10 million/repair. A high cost indicates >\$10 million/repair.

- Advantages - The advantages of each concept will be presented.

- Disadvantages - The disadvantages of each concept will be presented.

- Major equipment required - Any major pieces of equipment not normally in the base Civil Engineer's inventory will be presented.

- Additional research and development required - The areas where additional research and development will be required before a given concept could be deployed are identified. Based upon the present state-of-the-art, an estimate of the probability of success for each area of R&D identified will be presented.

Some of the concepts presented will have alternate materials and/or equipment that could be used instead of the primary system suggested. These systems will be presented in a similar manner following the primary system. In all cases the debris and upheaval should be used to partially fill the crater.

a. Concept 1. Rigid Cap Over Fill (See Figure 21.)

Procedure - The crater should be filled to within approximately 3 ft of the level of the original runway. During the backfilling of the crater, the debris should be sprayed continuously with a rapid setting cement using a jet slurry mixer or the equivalent. The amount of cement used should be approximately 10 percent by volume near the bottom of the crater and increased to near 25 percent as the fill reached a level of 3 ft below the surface of the original runway.

Next, well graded aggregate should be placed in the crater on top of the debris fill using front end loaders. Again, rapid setting cement should be sprayed on the aggregate as it is placed in the crater. The rate of application of the cement should be maintained at approximately one part of cement to three parts of aggregate. The surface should be leveled using a screed once the crater has been filled.

PRIMARY MATERIALS SUGGESTED

- Quick setting cement mixed with jet slurrier and sprayed on debris as it is placed in crater.

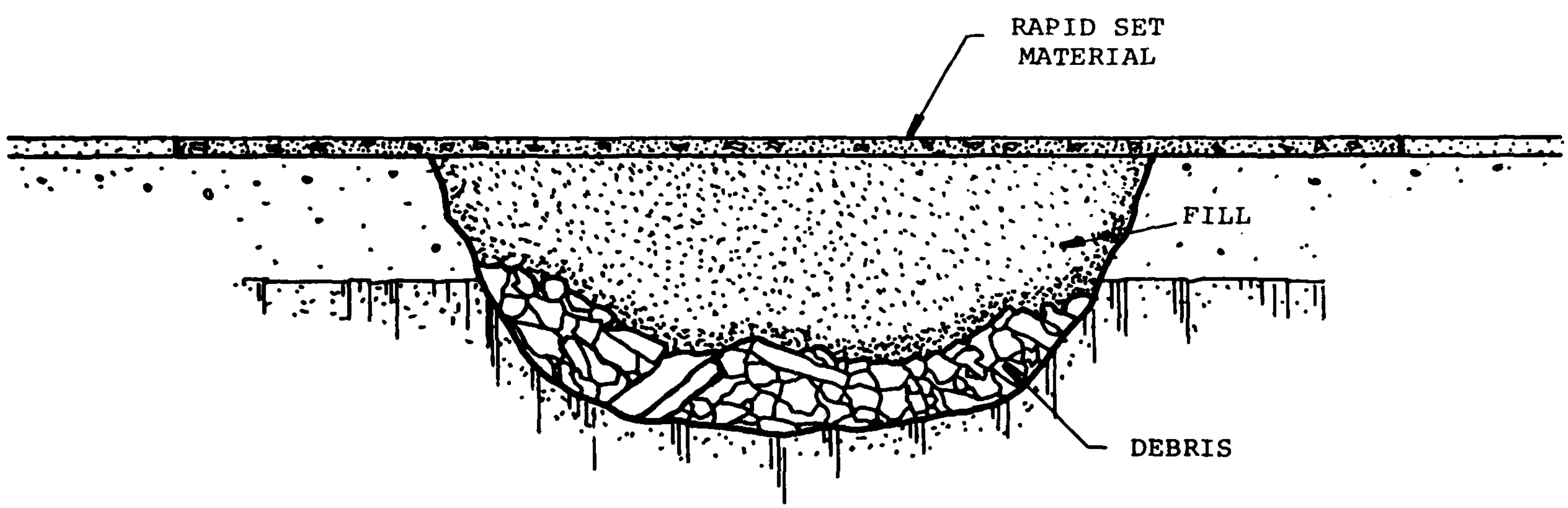


Figure 21. Concept 1

- Aggregate placed in crater by front end loaders after all debris has been placed. Aggregate to be sprayed with approximately 10 to 25 percent by volume of rapid set cement to consolidate fill.

Weight of Material Required to Fill 150 Yd^3

- 125 tons of quick setting cement
- 125 tons of aggregate

Cost

- Low

Advantages

- Easy to handle materials
- Long shelf life materials
- Inexpensive repair
- System can be used to fill both small and large craters

Disadvantages

- Very rapid mixing required ($\simeq$ 375 tons/hr)
- New or modified mixing equipment required
- Difficult to apply in subfreezing conditions

Major Equipment Required

- Jet slurrier or equivalent for cement

Additional Research and Development Required

- Modified cement mixing equipment; probability of success - high

ALTERNATE MATERIALS SUGGESTED

- Inorganics

  Quick setting cement alone
  Gypsum cement and aggregate
  Gypsum cement alone
  Fly ash and aggregate
  Fly ash alone
  Plaster and aggregate
  Plaster alone

Weight of Material Required to Fill 150 Yd^3

- 250 tons for binder alone systems, or

- 125 tons aggregate
- 125 tons binder

Cost

- Low

Advantages

- Easy to handle materials (all)
- Long shelf life materials (all)
- Inexpensive repair (all)
- Systems can be used to fill both small and large craters (all)

Disadvantages

- Very rapid mixing required (750 tons/hr for systems using binder alone)
- New or modified mixing equipment required (all)
- Difficult to apply in subfreezing conditions

Major Equipment Required

- Jet slurrier or equivalent for quick setting materials (all)

Additional Research and Development Required

- Modified binder mixing equipment; probability of success - high

ADDITIONAL ALTERNATE MATERIALS

- Organic

  Polyester polymer concrete and aggregate
  Furan polymer concrete and aggregate
  Methyl methacrylate and aggregate

Weight of Material Required to Fill a Volume of 150 Yd^3

- 160 tons of aggregate
- 45 tons of polymer

Cost

- Moderate to high

Advantages

- High flexural and compressive strengths
- Good adhesion
- Rapid hardening
- Can be applied in subfreezing conditions

Disadvantages

- Critical ingredient ratios
- Difficult to mix in large quantities or high rates
- Slower curing rates at low temperature
- High exotherm in thick sections
- Relatively short shelf life reported by manufacturers

Major Equipment Required

- High rate polymer mixing equipment

Additional Research and Development Required

- Modified field mixing equipment to obtain rates required; probability of success - moderate
- Reduction of exotherm by chemistry or heat sink additions; probability of success - moderate

b. Concept 2. Wet Sand Fill (See Figure 22.)

Procedure - In this concept wet sand would be pumped into the crater using a jet slurrier or a similar device to mix dry sand with water. The amount of water added would be enough to approach the saturation point and thus allow the sand to be self-compacting. The wet sand would be pumped into the crater as the debris is added so that all voids will be filled. Once the debris and wet sand have been used to fill the crater to the 3-foot level, only saturated sand should be added to the crater.

If desired, sand and graded aggregate could be added in equal volumes. The wet sand should still act as a self-compacting medium for the system. In either case, the repair should be rewet on a regular schedule so that the sand will always have the consistency of finely packed beach sand adjacent to the ocean.

PRIMARY MATERIALS

- Wet sand pumped into crater with jet slurrier, or
- Wet sand pumped into crater while aggregate is added

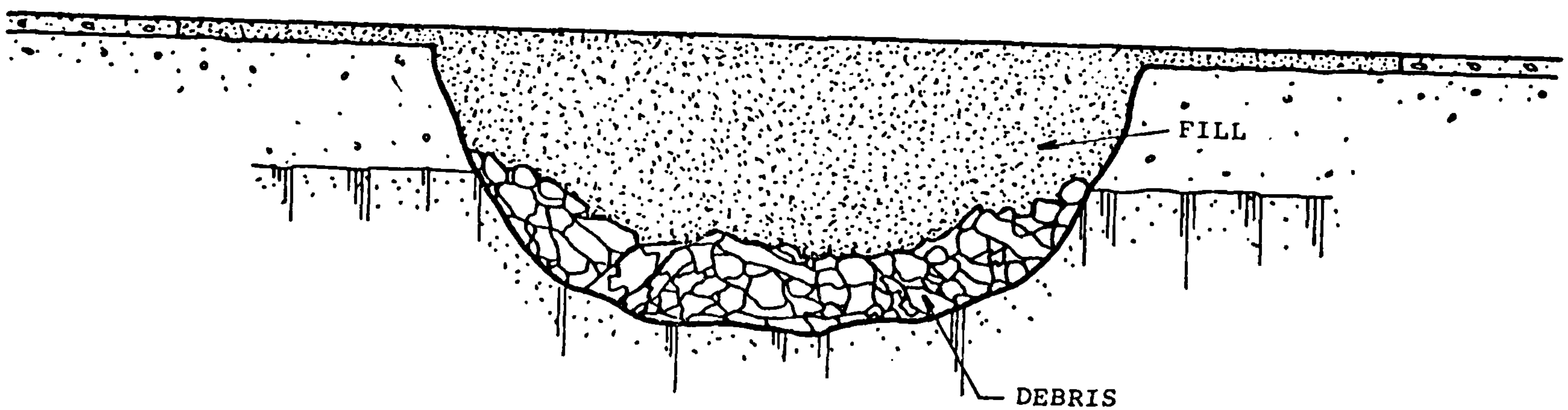


Figure 22. Concept 2

Weight of Material Required to Fill a Volume of 150 Yd^3

- 250 tons of sand and water, or
- 125 tons of aggregate
- 125 tons of wet sand

Cost

- Low

Advantages

- Very low cost repair
- Easy to install
- Easy to maintain

Disadvantages

- Requires constant observation and frequent rewetting
- May have difficulty in supporting load if allowed to dry
- May cause Foreign Object Damage (FOD) if wheel fenders, covers, or mud deflectors are not installed on aircraft

Equipment Required

- Jet slurrier or equivalent mixer for sand

Additional Research and Development Required

- Amount of water required to obtain self-compacting sand; probability of success - high
- Amount of moisture required to support aircraft; probability of success - high
- Equipment for pumping up to 750 tons/hr of sand slurry; probability of success - high

c. Concept 3. Cereal Bowl System (See Figure 23.)

Procedure - Debris is added to the crater until it is filled to within approximately 4 feet of the original runway level. During the back-filling process a self-hardening fly ash should be sprayed on the debris. Sufficient fly ash should be used to consolidate the debris. Then a 6- to 12-inch-thick layer of self-hardening fly ash mixed with the proper amount of water should be sprayed on the debris and up the sides of the crater forming a bowl-like configuration. Then well-graded aggregate should be added to fill the crater to within 8 to 12 inches of the original runway level. During the aggregate filling process, self-hardening fly ash should be sprayed on the aggregate to help consolidate it. The amount of fly ash should not exceed 25 percent by volume.

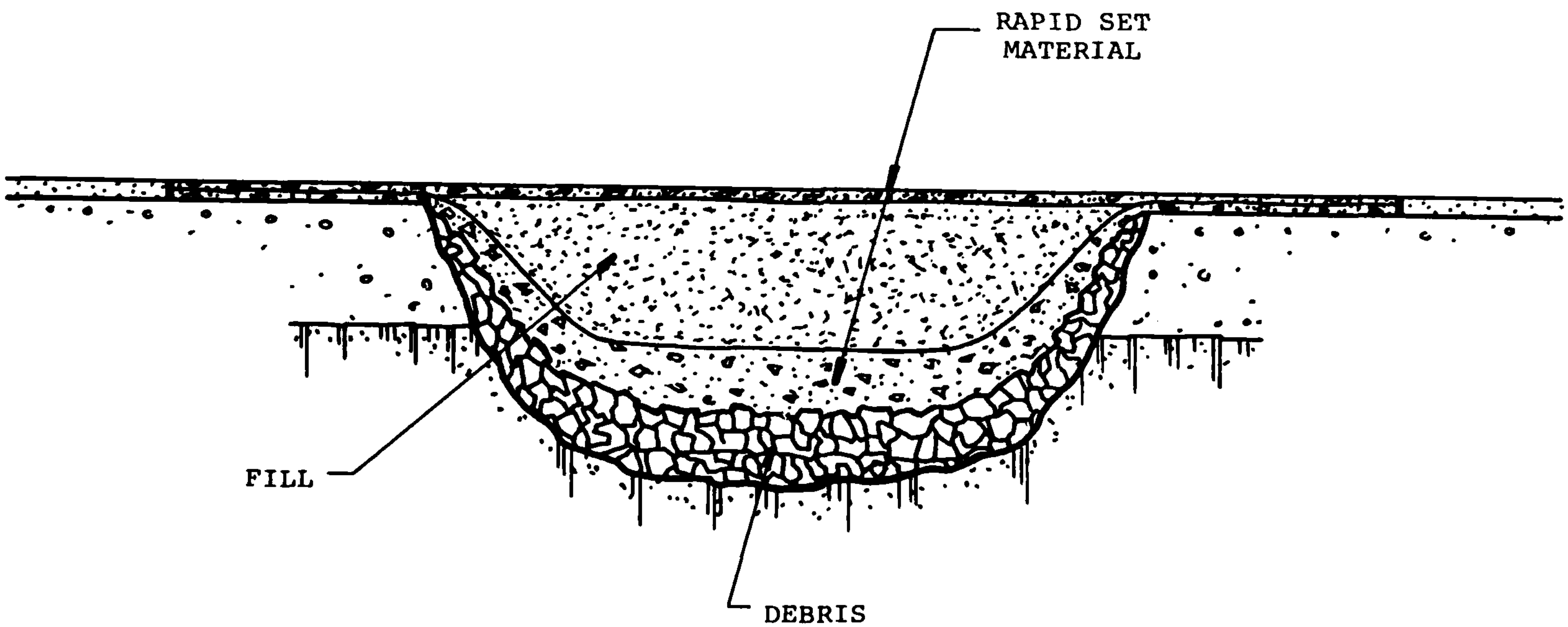


Figure 23. Concept 3

The cap should be formed with a rich mixture of fly ash and aggregate. Once the crater is filled, it should be leveled with a screed.

PRIMARY MATERIALS

- Self-hardening fly ash mixed with water and sprayed into the crater as the debris is added
- Well graded aggregate

Weight of Material Required to Fill a Volume of 150 Yd^3

- 175 tons of fly ash
- 75 tons of graded aggregate

Cost

- Low

Advantages

- Easy to handle materials
- Long shelf life materials
- Inexpensive repair
- System can be used to fill both small and large craters
- The double layer of binder less likely to rut during repeated operation

Disadvantages

- Very rapid mixing required (525 tons/hr)
- High speed mixing equipment required
- Difficult to apply during subfreezing conditions

Major Equipment Required

- High speed mixer

Additional Research and Development Required

- Modified cement mixing equipment; probability of success - high

ALTERNATE MATERIALS

- Inorganics

  Quick setting cement and aggregate or wet sand
  Gypsum cement and aggregate or wet sand
  Plaster and aggregate

Weight of Material Required to Fill a Volume of 150 Yd^3

- 175 tons of binder
- 75 tons of filler

Cost

- Low

Advantages

- Easy to handle materials
- Long shelf life materials
- Inexpensive repair
- System can be used to fill both small and large craters
- The double layer of binder less likely to rut during repeated operation

Disadvantages

- Very rapid mixing required (525 tons/hr)
- High speed mixing equipment required
- Difficult to apply during subfreezing conditions

Major Equipment Required

- High speed mixer

Additional Research and Development Required

- Modified cement mixing equipment; probability of success - high

ADDITIONAL ALTERNATE MATERIALS

- Organic

    Polyester polymer concrete and aggregate
    Furan polymer concrete and aggregate or wet sand
    Methyl methacrylate and aggregate or set sand

Weight of Material Required to Fill a Volume of 150 Yd^3

- 60 tons of polymer
- 150 tons of graded aggregate

Cost

- Moderate to high

Advantages

- Thinner section of polymer can be used for both the lower and the cap layers because of increased flexural strength
- Good adhesion to base material and adjacent runway
- Rapid hardening
- Can be applied in subfreezing weather

Disadvantages

- Critical ingredient ratios
- Difficult to mix in large quantities and at high rates
- High exotherm in thick sections
- Relatively short shelf life

Major Equipment Required

- High rate polymer mixing equipment

Additional Research and Development Required

- New field mixing equipment; probability of success - moderate
- Reduction of exotherm by chemistry or heat sink additions; probability of success - moderate

d. Concept 4A. Thin Fiberglass Mat Over Rigid Cap (See Figure 24.)

Procedure - A thin 1/2- to 3/4-inch-thick prefabricated fiberglass-reinforced polyester mat would be added to either concept 1 or 3. The dimension of the mat could be either a 70-foot diameter or 70-foot square. It is anticipated that it would be transported to the repair site by helicopter in one piece or by a flatbed truck in multiple sections. The single piece system would be preferred because it would not require assembly at the site. After the mat is laid or towed into position, it would be bonded to the runway around the edges with a fast setting epoxy adhesive or nailed in position with an explosively driven hammer.

The primary purpose for the thin mat is to distribute the load of the aircraft during the initial few hours of operation before the cap and repair system have had sufficient time to develop full strength. After the first 24 hours of operation, the mat could be removed and any minor rutting of the cap could be repaired.

PRIMARY MATERIALS

- A thin 1/2-inch to 3/4-inch-thick prefabricated fiberglass/polyester mat is added to concepts 1 and 3.

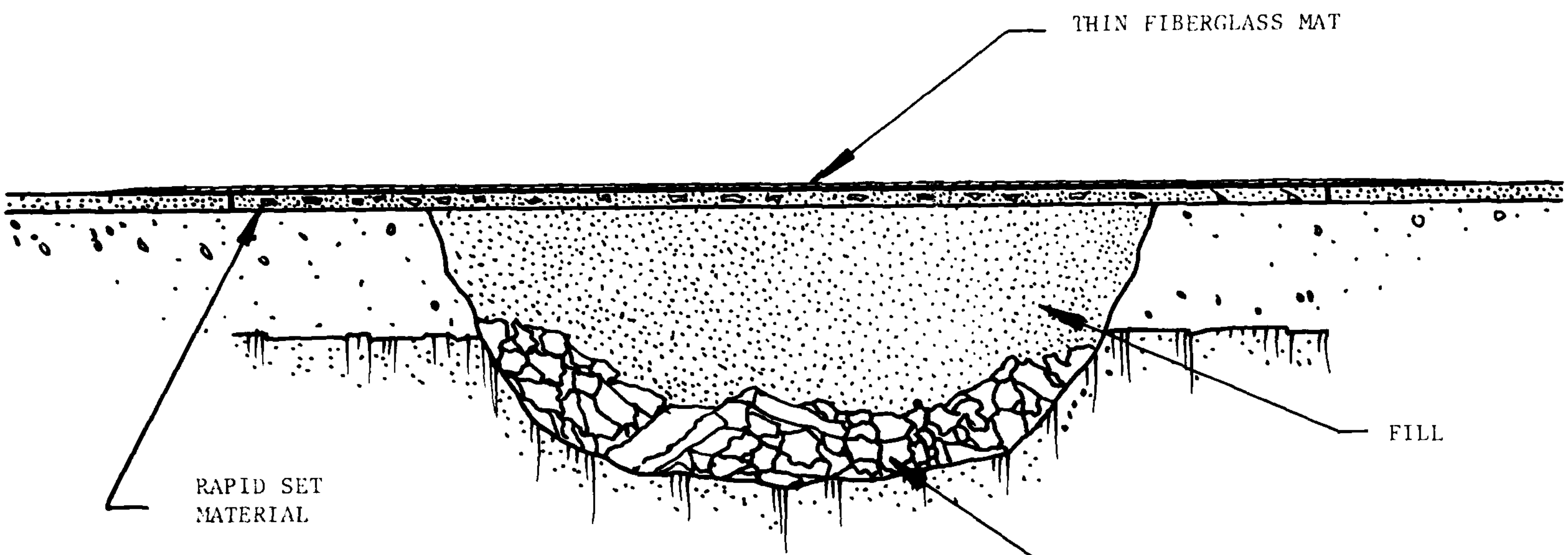


Figure 24. Concept No. 4A

Weight of Material Required to Fill a Volume of 150 Yd^3

- 7- to 10-ton mat

Cost

- Low to moderate

Advantages

- Allows the base material to cure
- Allows the repair to be used as soon as the mat is put in place

Disadvantages

- Requires installation of large mat

Major Equipment Required

- Prefabricated mat

Additional Research and Development Required

- Method of handling and installing large air-delivered mat; probability of success - high
- Ability of aircraft to take off and land on runway containing mat-covered repairs; probability of success - moderate

e. Concept 4B. Thin Fiberglass Mat Over Wet Sand Fill

Procedure - In this concept the same fiberglass-reinforced polyester mat design described in concept 4A could be used to cover the wet sand fill described in concept 2. The primary purpose of this mat would be to distribute the aircraft load. In addition, the mat would drastically reduce the loss of moisture from the sand due to evaporation; however, a water distribution system would have to be installed under the mat to replenish the water that would naturally drain from the sand. The mat would be anchored around the perimeter to the existing runway and would remain in place for the entire two-week period. (See Figure 25.)

PRIMARY MATERIALS

- A thin prefabricated fiberglass/polyester mat is added to concept 2.

Weight of Material Required to Fill a Volume of 150 Yd^3

- 7 to 10 tons

Cost

- Low to moderate

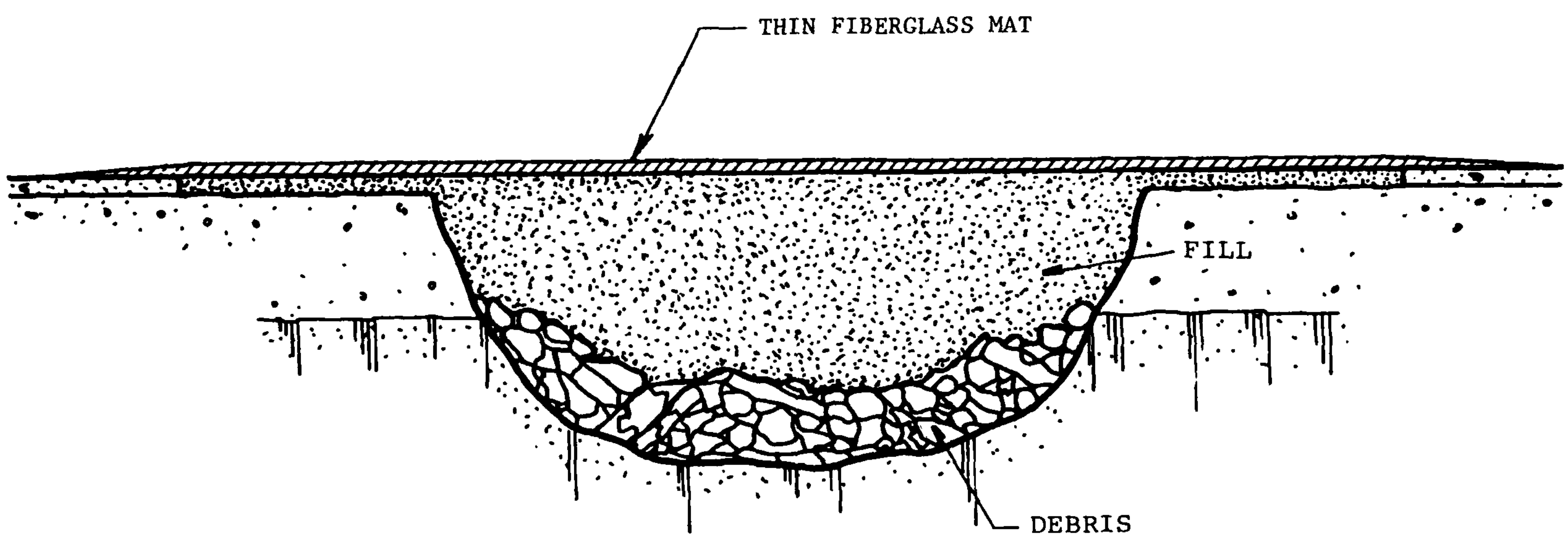


Figure 25. Concept 4B

Advantages

- Prevention of rutting
- Reduction of evaporation
- Reduction in foreign object damage to the aircraft

Disadvantages

- Requires installation of mat

Major Equipment Required

- Prefabricated mat

Additional Research and Development Required

- Method of handling and installation of large mat; probability of success - high
- Ability to launch and recover aircraft over a mat-covered wet sand filled repair; probability of success - moderate

f. Concept 5. Membrane Support System (See Figure 26.)

Procedure - This concept utilizes two or three fabric membranes to help support and distribute the concentrated wheel load of the aircraft. A precut fabric membrane made of Kevlar®, dacron®, or nylon® would be draped over the debris before wet sand or graded aggregate fill would be added to the crater. Additional membranes would be added each 12 to 18 inches. The membranes would effectively increase the CBR of the fill without having to compact the material. A quick setting inorganic binder should be sprayed on the debris and fill materials to consolidate the system. The same quick setting binder should be mixed with aggregate to form the cap.

PRIMARY MATERIALS

- Wet sand and/or graded aggregate
- 2 to 3 fabric membranes to increase effective CBR without compaction (preferred fabric - Kevlar® alternates dacron® or nylon®)
- Quick setting inorganic binder

Weight of Material Required to Fill a Volume of 150 Yd^3

- Each fabric membrane will weigh between 150 and 200 lb
- 150 tons of aggregate or wet sand
- 100 tons of inorganic binder

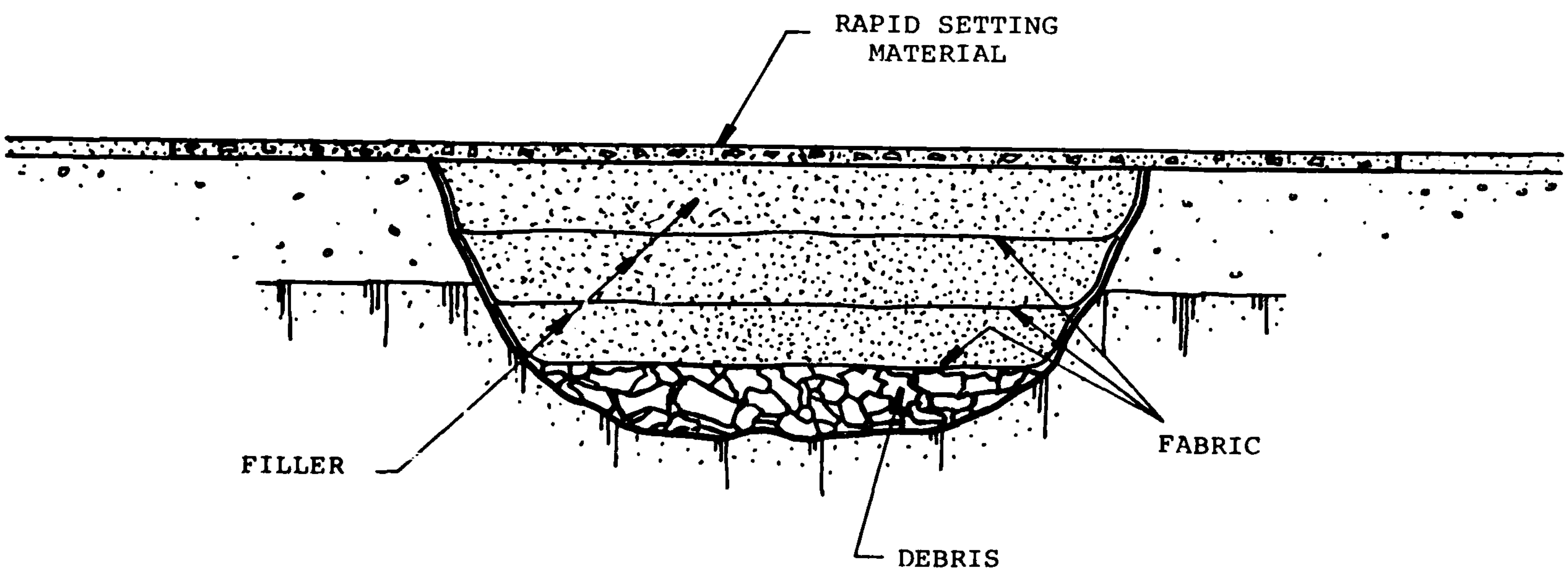


Figure 26. Concept 5

Cost

- Low

Advantages

- Increased CBR
- Easy to handle materials

Disadvantages

- Increased time required because of installation of fabric membrane
- Rapid mixing of cap material required (600 tons/hr)
- Difficult to apply in subfreezing conditions

Major Equipment Required

- Rapid mixing equipment

Additional Research and Development Required

- Evaluation of effect of fabric membrane; probability of success - high
- High speed mixing equipment; probability of success - high

ALTERNATE MATERIALS

- Replacement quick setting inorganic binder with inorganic binder, such as:

  Furan polymer concrete
  Polyester polymer concrete
  Polyester
  Polyurethane (ISP)
  Methyl Methacrylate

Weight of Material Required to Fill a Volume of 150 Yd^3

- Each fabric membrane will weigh between 150 and 200 lb
- 160 tons of aggregate or wet sand
- 50 tons of organic binder

Cost

- Moderate to high

Advantages

- High flexural and compressive strength
- Good adhesion
- Rapid hardening
- Can be applied in subfreezing weather

Disadvantages

- Critical ingredient ratios
- Difficult to mix in large quantities or high rates
- High exotherm in thick sections
- Relatively short shelf life reported

Major Equipment Required

- High rate polymer mixing equipment

Additional Research and Development Required

- Modified field mix equipment to obtain rates required; probability of success - moderate
- Reduction of exotherm by chemistry or heat sink additions; probability of success - moderate

g. Concept 6. Expanded Material and Binder System (See Figure 27.)

Procedure - In this concept quick setting cement mixed in a high speed jet slurrier would be sprayed on the debris as it is placed in the crater. Expanded polystyrene beads would be pneumatically mixed with the cement to form a low density material. Initially, the ratio of foam to cement would be high so that a low density binder would be placed in the bottom of the crater. The ratio would be decreased as the fill material approaches the top of the crater so that a stronger, higher density material would be placed near the surface of the repair. Graded aggregate and cement slurry should be used to fill approximately the top one-third of the crater. There are a number of foams and binders that could be used with this concept. Several of the combinations are presented with this concept.

PRIMARY MATERIALS

- Expanded polystyrene foam beads
- Graded aggregate
- Quick setting cement

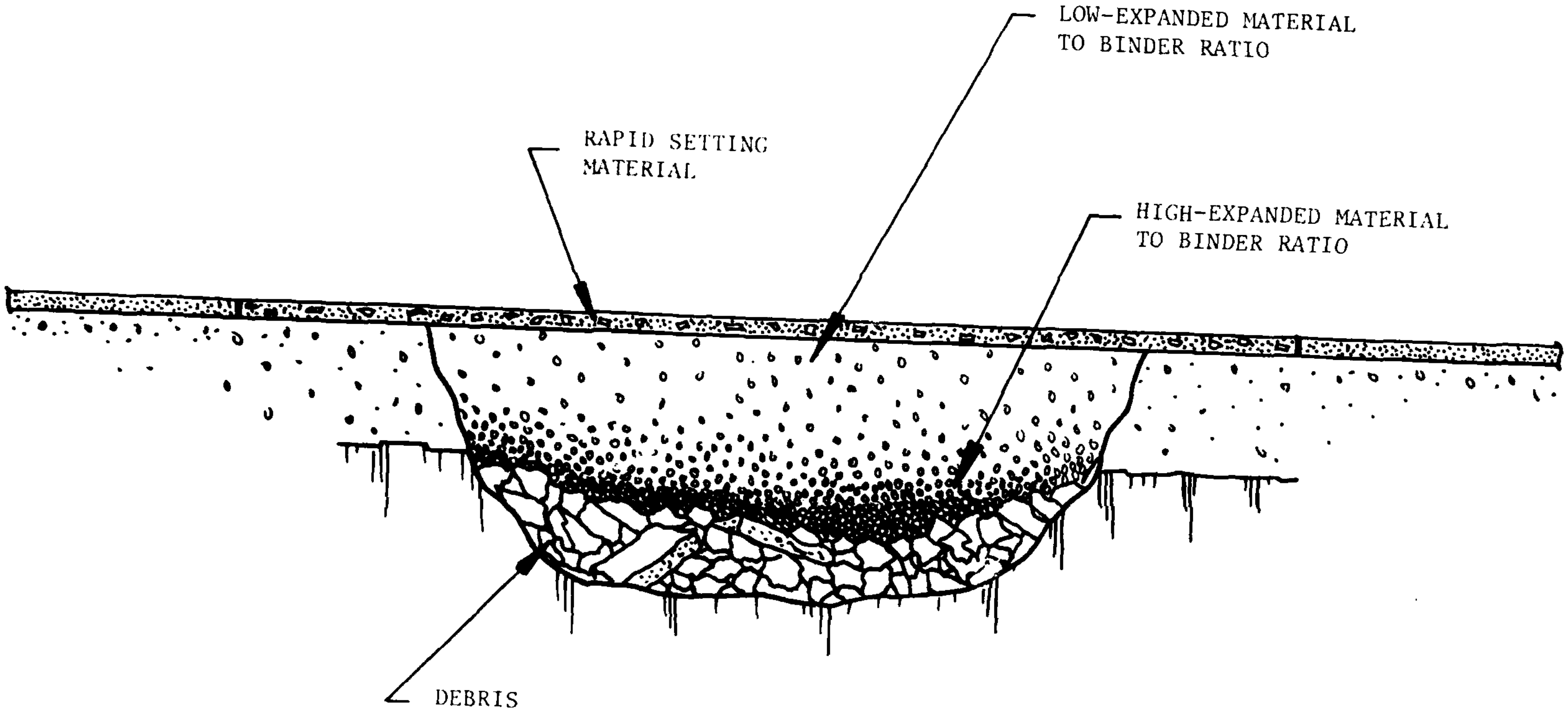


Figure 27. Concept No. 6

Weight of Material Required to Fill a Volume of 150 Yd^3

- 3 tons of polystyrene beads
- 100 tons of quick setting cement
- 60 tons of graded aggregate

Cost

- Low

Advantages

- Easy to handle materials
- Long shelf life materials
- Inexpensive repair
- System can be used to fill both small and large craters
- Low density foam easy to store and mix

Disadvantages

- Very rapid mixing required (up to 500 tons/hr)
- New or modified mixing equipment required
- Difficult to apply in subfreezing conditions
- Foam beads may float and cause stratification problems

Major Equipment required

- Jet slurrier or equivalent for cement
- Pneumatic system for polystyrene beads

Additional Research and Development Required

- Modified cement mixing equipment; probability of success - high
- Pneumatic mixer for foam beads; probability of success - high

ALTERNATE MATERIALS

- Expanded polystyrene foam beads
- Inorganic binders

  Gypsum cement
  Fly ash
  Plaster

- Graded aggregate

Weight of Material Required to Fill a Volume of 150 Yd^3

- 3 tons polystyrene beads
- 100 tons binder
- 60 tons graded aggregate

Cost

- Low

Advantages

- Easy to handle materials (all)
- Long shelf life materials (all)
- Inexpensive repair (all)
- Systems can be used to fill both small and large craters (all)
- Lightweight fill material

Disadvantages

- Very rapid mixing required (up to 750 tons/hr)

Major Equipment Required

- Jet slurrier or equivalent for quick setting inorganics
- Pneumatic system for polystyrene beads

Additional Research and Development Required

- Mixing equipment for binder; probability of success - high
- Mixer for beads; probability of success - high

ALTERNATE MATERIALS

- Expanded polystyrene foam beads
- Organic binders

    Furan
    Methyl Methacrylate
    Epoxy
    Aminos

- Graded aggregate

Weight of Material Required to Fill a Volume of 150 Yd^3

- 3 tons of polystyrene beads
- 60 tons of polymer
- 60 tons of graded aggregate

Cost

- Moderate to high

Advantages

- High flexural and compressive strengths
- Good adhesion
- Rapid curing
- Can be used in subfreezing conditions

Disadvantages

- Critical mixing ratios
- Difficult to mix in large quantities and high rates
- Slower curing rates at low temperature
- High exotherm in thick sections
- Relatively short shelf life reported by manufacturers

Major Equipment Required

- High rate polymer mixing equipment
- Pneumatic system for polystyrene beads

Additional Research and Development Required

- High speed polymer mixing equipment; probability of success - moderate
- Reduction of exotherm by formulation or heat sink addition; probability of success - moderate
- Moisture resistance; probability of success - moderate

ADDITIONAL ALTERNATE MATERIAL COMBINATIONS

- Inorganic fill - specially designed and formed spheres made from:

Cements
Clay
Pumice

- Inorganic binder

  Quick setting cement
  Gypsum cement
  Fly ash
  Plaster

- Organic binder

  Polyester
  Furan
  Methyl Methacrylate
  Epoxy

Weight of Material Required for 150 Yd^3

- 125 tons inorganic or 45 tons of polymer
- 100 tons filler

Cost

- Low to high

Advantages

- Can be designed for maximizing compaction
- Excellent adhesion
- Reduced moisture problems
- Proper configuration for a better mix
- Matched density to reduce stratification
- Long shelf life

Disadvantages

- Must be foamed and shipped to each base in the expanded configuration

Major Equipment Required

- Equipment to mix filler with binder

Additional Research and Development Required

- Design special inorganic spheres; probability of success - high

- Develop equipment to mix filler and binder at required rates; probability of success - moderate

ADDITIONAL ALTERNATE MATERIAL COMBINATIONS

- Organic fill - specially designed and molded plastic spheres made from:

  Thermoplastics

  Acrylics
  Polycarbonates
  PVC

- Inorganic binder

  Quick setting cement
  Gypsum cement
  Fly ash
  Plaster

- Organic binder

  Polyester
  Furan
  Methyl Methacrylate
  Epoxy

Weight of Material Required to Fill a Volume of 150 Yd^3

- 45 tons of plastic spheres
- 125 tons of inorganic binder or 60 tons of polymer

Cost

- Moderate to high

Advantages

- Can be designed to maximize compaction
- Excellent adhesion
- Reduced moisture problems
- Proper configuration for a better mix
- Matched density to reduce stratification
- Long shelf life

Disadvantage

- Must be molded and shipped to each base

Major Equipment Required

- Equipment to mix filler and binder

Additional Research and Development Required

- Design special plastic spheres; probability of success - high

h. Concept 7. Liquid Filled Bags with Binder System (See Figure 28.)

Procedure - Quick setting cement would be sprayed on the debris as it is placed in the crater. Once the debris and binder had filled the crater to within 4 ft of the original surface, water-filled bags would be placed in the crater. A tough, puncture-resistant vinyl or polyethylene film should be used to fabricate the bags. The bags could be filled and sealed on site. Then they could be introduced into the crater with a specially designed conveyor belt system. The bags would occupy between 60 and 80 percent of the volume of the crater not occupied by the debris or cap. Quick setting cement would be used to fill the space between the bags and also form the cap.

PRIMARY MATERIALS

- Water-filled bags
- Inorganic binders

    Gypsum cements
    Fly ash
    Plaster

Weight of Material Required to Fill a Volume of 150 Yd^3

- 22,000 gallons of water-filled bags
- 80 tons of binder

Cost

- Low

Advantages

- Easy to handle materials (all)
- Long shelf life (all)
- Inexpensive repair (all)
- Can be used for small and large crater repair
- Less binder material required

Disadvantages

- Difficult to use in subfreezing conditions

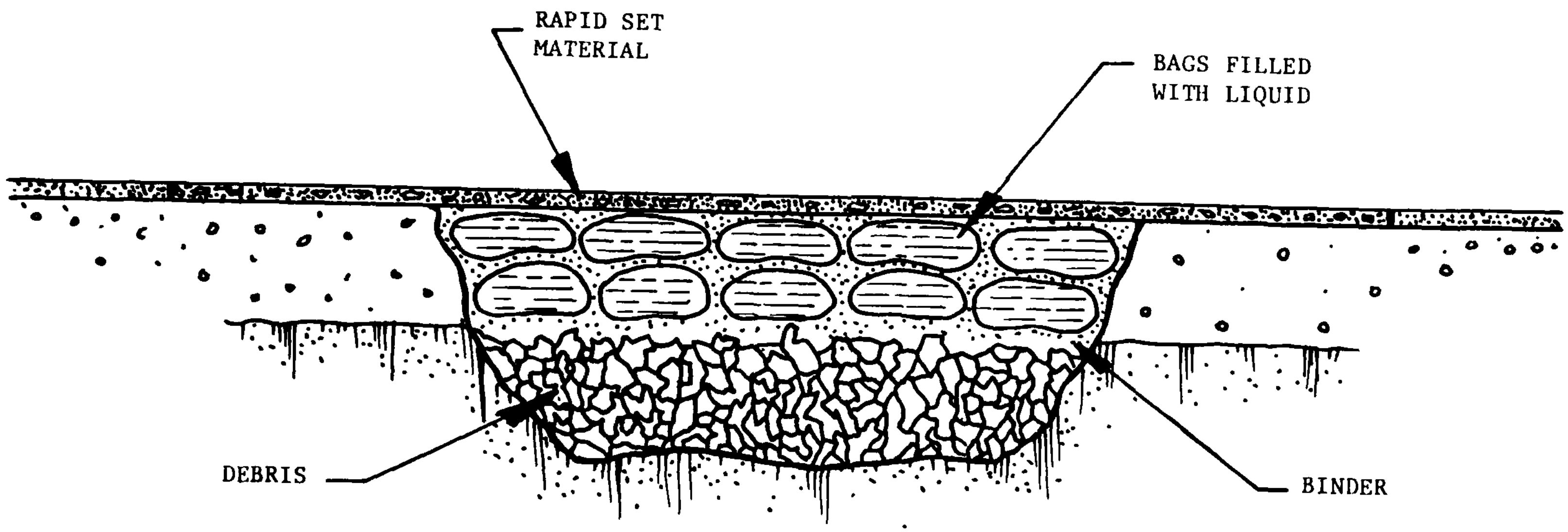


Figure 28. Concept 7

- Rapid mixing equipment needed (300 tons/hr)

Major Equipment Required

- Bag filling and sealing equipment
- Conveyor system for water bags
- Binder mixing equipment

Additional Research and Development Required

- Bag filling and sealing equipment; probability of success - high
- Water bag conveyor system; probability of success - high
- Water bag design; probability of success - high
- Mixing equipment for binder; probability of success - high

ADDITIONAL MATERIALS

- Water-filled bags
- Organic binders

  Furans
  Polyesters
  Polyurethanes
  Aminos
  Methyl Methacrylate
  Epoxy

Weight of Material Required to Fill a Volume of 150 Yd^3

- 22,000 gallons of water bags
- 45 tons of polymer

Cost

- Moderate to high

Advantages

- Water bags act as heat sink for polymer
- High flexural and compressive strengths
- Good adhesion
- Rapid curing
- Can be used in subfreezing if water is modified

Disadvantages

- Critical mixing ratios
- Difficult to mix in large quantities and high rates
- Slower curing rates at low temperatures
- High exotherm in thick sections
- Relatively short shelf life as reported by manufacturers

Major Equipment Required

- Base filling and sealing equipment
- Conveyor system for bags
- High rate polymer mixing equipment

Additional Research and Development Required

- High speed polymer mixing equipment; probability of success - moderate
- Reduced exotherm and better moisture-resistant polymer; probability of success - moderate
- Water bag conveyor system; probability of success - high
- Water bag filling and sealing equipment; probability of success - high

i. Concept 8. Sand-Filled Bags with Binder System (See Figure 29.)

Procedure - In this concept sand bags are used to fill part of the crater. Debris would be placed in the bottom of the crater with a quick setting inorganic binder to help consolidate the backfill. After about two-thirds of the crater is filled with debris and binder, sand-filled bags should be placed in the crater. The space between the sand bags should be filled with the same inorganic binder used to consolidate the debris. The sand bags can be either prefilled or filled automatically at the site. The sand bags may be placed in the crater using a conveyor belt system.

The cap could be formed using the same quick setting inorganic binder used to consolidate the debris and sand bag system.

PRIMARY MATERIALS

- Sand bags

Weight of Material Required to Fill a Volume of 150 Yd^3

- Approximately 2000 - 100-lb sand bags required
- 125 tons of inorganic binder

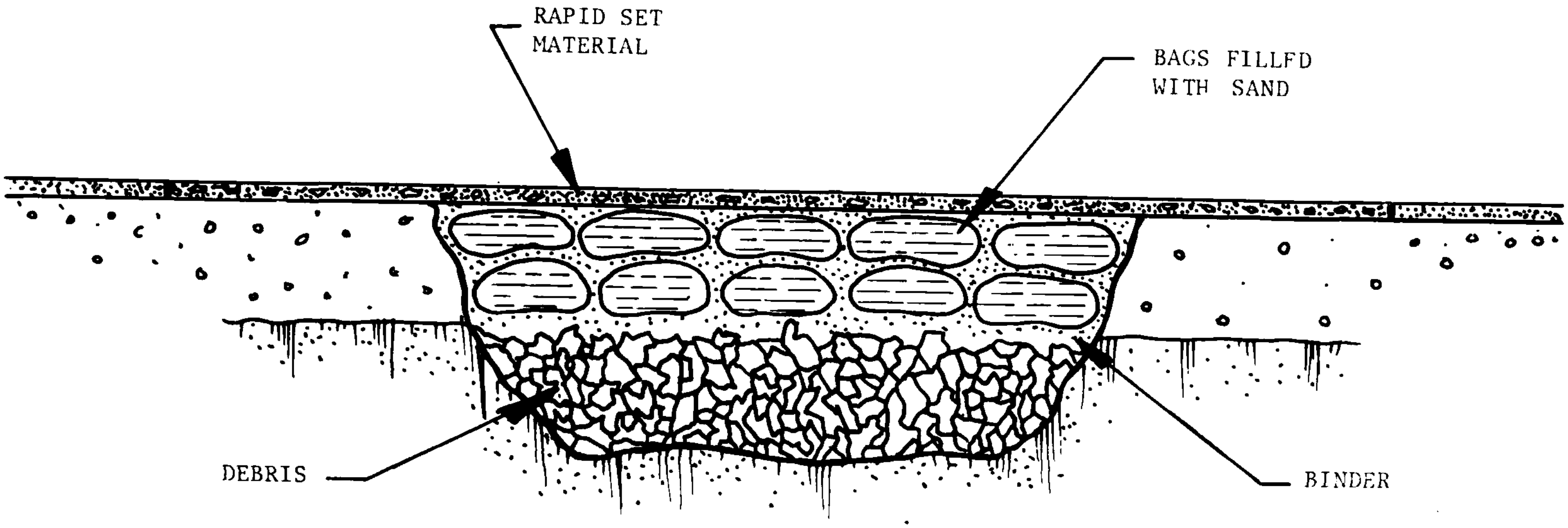


Figure 29. Concept No. 8

Cost

- Low to moderate

Advantages

- Good consolidation of fill material
- Easy to handle materials
- System may be used to fill both small and large craters
- Long shelf life

Disadvantages

- Very rapid mixing required
- New or modified mixing equipment required
- Difficult to apply in subfreezing weather
- Large number of sand bags need to be filled and handled

Major Equipment Required

- High speed mixing equipment
- Automatic sand bag filling and handling equipment

Additional Research and Development Required

- Modified mixing equipment; probability of success - high
- Automatic sand bag filling and handling equipment; probability of success - moderate

ALTERNATE MATERIALS

- Sand bags
- Organic binder and cap material

    Polyester
    Polymer concrete
    Methyl Methacrylate

Weight of Material Required to Fill a Volume of 150 Yd^3

- Approximately two thousand 100-lb bags required
- 60 tons of polymer

Cost

- Moderate to high

Advantages

- High flexural and compressive strengths
- Good consolidation of fill
- Can be applied in subfreezing weather

Disadvantages

- Very rapid mixing required
- Large number of sand bags required
- High exotherm in thick sections
- Relatively short shelf life
- Critical ingredient ratio

Major Equipment Required

- High rate polymer mixer
- Automatic sand bag filling and handling equipment

Additional Research and Development Required

- Modified mixing equipment; probability of success - moderate
- Automatic sand bag filling and handling equipment; probability of success - moderate

j. Concept 9. Foam Filled with Rigid Cap (See Figure 30.)

Procedure - In this concept an organic foam material would be used to fill part of the crater. The most widely used organic foam-in-place material is polyurethane. This material has an excellent expansion ratio that can be controlled within reason. The foaming agents could be sprayed on the debris as it is being introduced into the crater. This material would expand to fill any voids that may occur, and it has excellent adhesion to most material. The top 3 to 4 feet of the fill should be foam with a lower density foam in the bottom and a higher density, stronger foam in the top half of the fill. The density of the foam may be easily controlled by the ratio of the two components used to make the foam.

The cap would be made of a quick setting inorganic or organic binder.

PRIMARY MATERIALS

- Foamed in place polyurethane
- Inorganic binder cap, or
- Organic binder cap

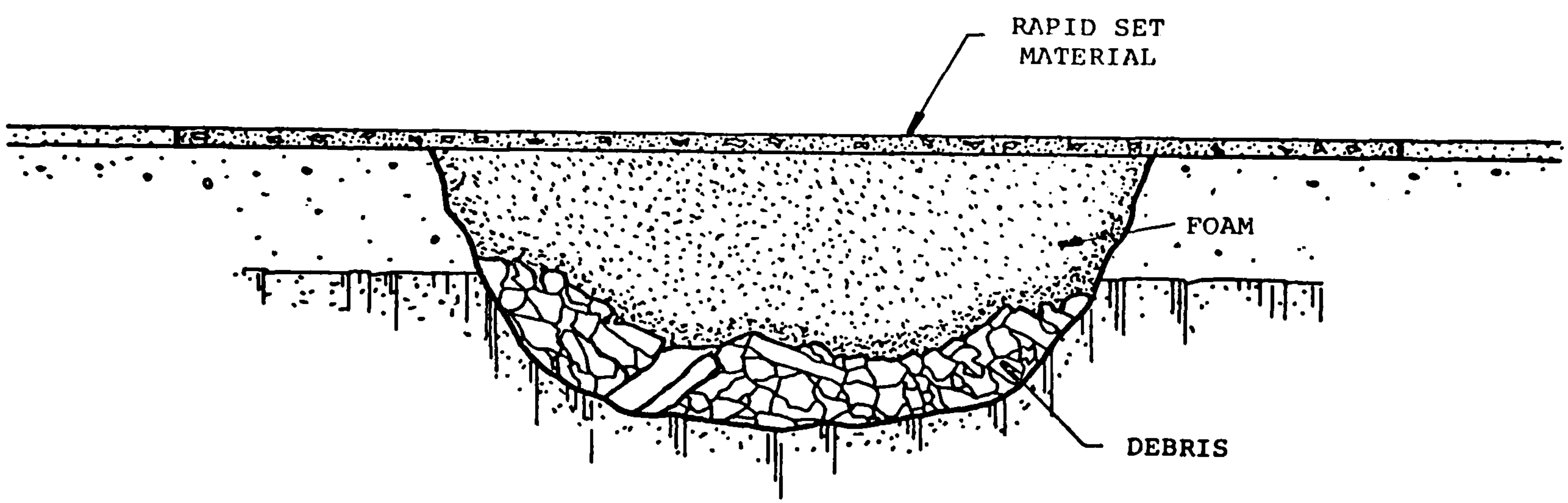


Figure 30. Concept 9

Weight of Material Required to Fill a Volume of 150 Yd^3

- 20,000 lb of foam in place polyurethane
- 100 tons of inorganic binder, or
- 60 tons of organic binder

Cost

- Low to moderate

Advantages

- Commercially available foaming equipment
- Light weight fill material
- Low storage volume required for fill material
- Foamable in place

Disadvantages

- High exotherm - could be self-destructive
- High to moderate flammability
- Difficult to control density when spraying in large volumes and at high rates
- Short shelf life
- Irregular contoured surface after foaming
- Affected by adverse weather

Major Equipment Required

- High speed foaming equipment
- High speed mixing equipment

Additional Research and Development Required

- Reduction of exotherm so that thick sections may be generated; probability of success - low
- High speed mixing equipment; probability of success - high
- High rate foaming equipment; probability of success - moderate

k. Concept 10. Portable Deck Over Fill System (See Figure 31.)

Procecure - In this concept a portable deck would serve as the new runway surface in the area of the repair. The deck would serve as the new runway surface in the area of the repair. The deck would be flush with the adjacent, original runway surface. The debris and graded aggregate would be consolidated with either an organic or inorganic binder material.

The deck would be assembled from prefabricated panels having specific dimensions. As a result, the shape and size of finished deck would be a multiple of the individual panels. Therefore, the concrete around the crater would have to be cut or broken along specific, precise straight lines so that when the concrete inside the cuts was removed the finished decks would fit.

There are several ways that the concrete may be cut along precise lines; however, none of the methods are very fast. These methods include diamond saws and tungsten carbide tipped wheels. Another method that might be faster involves a tool called a rocksplitter manufactured by the Darda Corporation of West Germany. This device is basically a hydraulic-actuated wedge. The wedge is placed in closely fitting drilled holes. The wedge is then expanded until the rock or concrete cracks. The direction of the crack may be controlled by the orientation of the wedge. If several holes are drilled along a straight line and rocksplitters are placed in adjacent holes with the wedges aligned, the concrete should crack along the predetermined line.

One activity associated with this operation that would require a considerable amount of time would be the drilling of the holes. In order to reduce the time required to drill the holes along the desired path, a multiple drilling system similar to the one shown in Figure 32 could be constructed and used. This unit could drill 5 or more holes at one time and then be moved to the next position for drilling while the concrete was being broken between the previous set of drilled holes with the rocksplitter system.

After the concrete has been broken, it may be removed from the crater or used as part of the backfill. The fill material would be placed in the crater until it reaches a level approximately equal to the thickness of the deck. Then a screed, designed to fit into the cavity in the runway, should be used to level the fill to the prescribed depth so that the deck will be flush with the adjacent runway.

The deck could be assembled adjacent to the crater and towed into position or assembled in position. The preassembled system would reduce the total installation time; however, it may be difficult to tow the large, thick deck into the exact location desired.

The space between the deck and the original runway should be filled with the same quick setting compound used to consolidate the fill material so that the transition is smooth.

PRIMARY MATERIALS

- Aluminum deck, or
- Steel deck, or

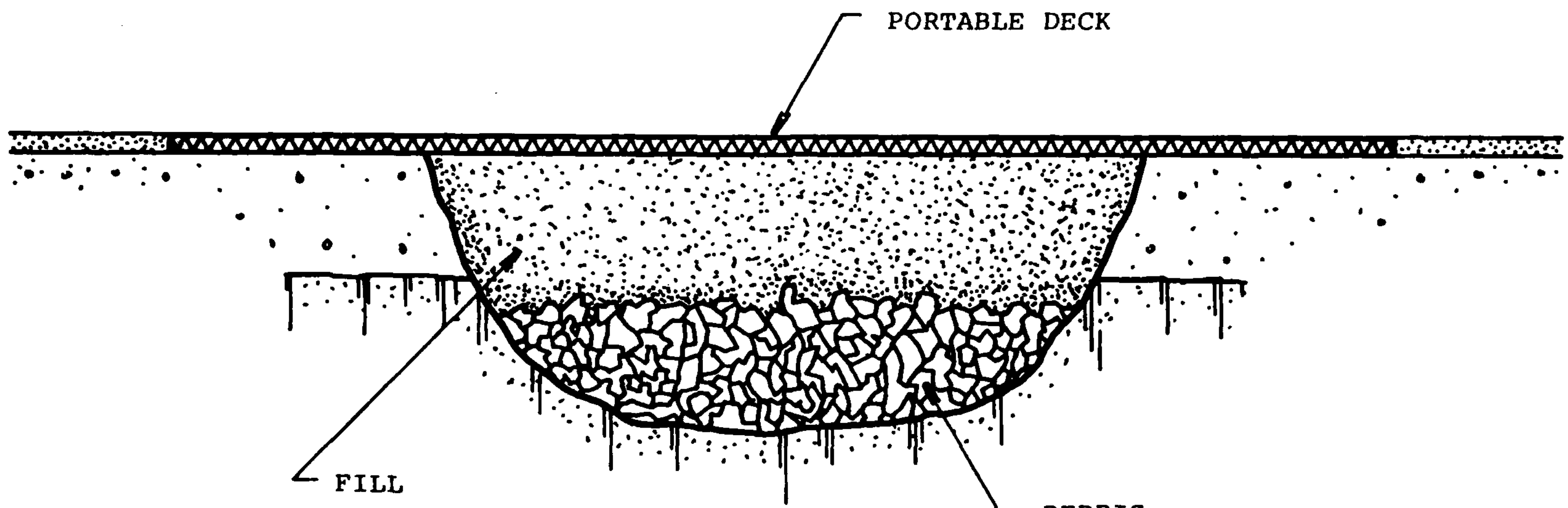


Figure 31. Concept 10

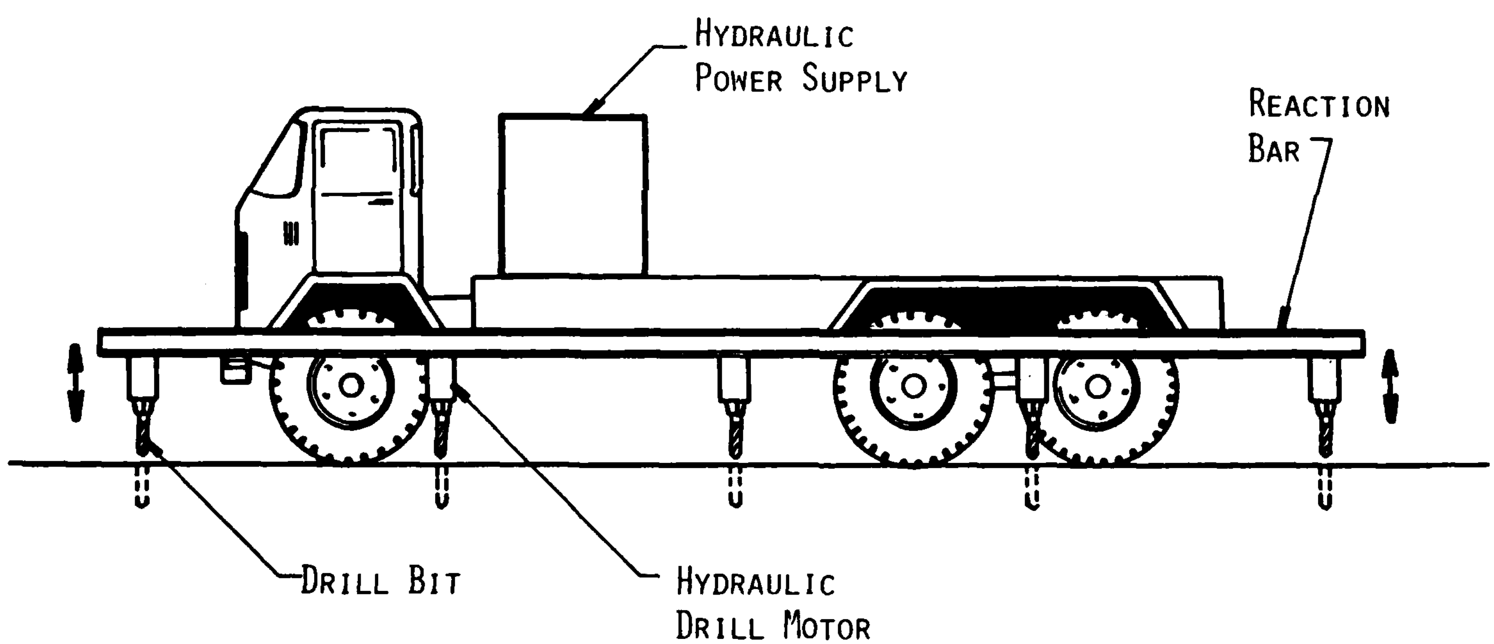


Figure 32. Multiple Drill Unit

- Fiberglass/polyester deck
- Sand or graded aggregate

<u>Weight of Material Required to Fill a Volume of 150 Yd^3</u>

- 25 tons of deck material (aluminum), or
- 50 tons of deck material (for steel), or
- 30 tons of deck material (for fiberglass/polyester)
- 200 tons of fill material

<u>Cost</u>

- Moderate

<u>Advantages</u>

- Standard construction techniques can be used to fabricate the decks
- Easy to install
- Prefabricated construction
- Can be installed at all temperatures
- Excellent runway surface available

<u>Disadvantages</u>

- May take over one hour to install
- Deck may be damaged while handling
- Difficult to be certain that deck will be supported uniformly along entire length

<u>Major Equipment Required</u>

- Deck
- Helicopter crane equipment

<u>Additional Research and Development Required</u>

- Deck; Probability of success - high
- Installation procedures; probability of success - high

1. <u>Concept 11.</u> <u>Ice Rink System</u> (See Figure 33.)

<u>Procedure</u> - In this concept, debris, wet sand, and graded aggregate may be used to fill the crater to within approximately 6 inches of the

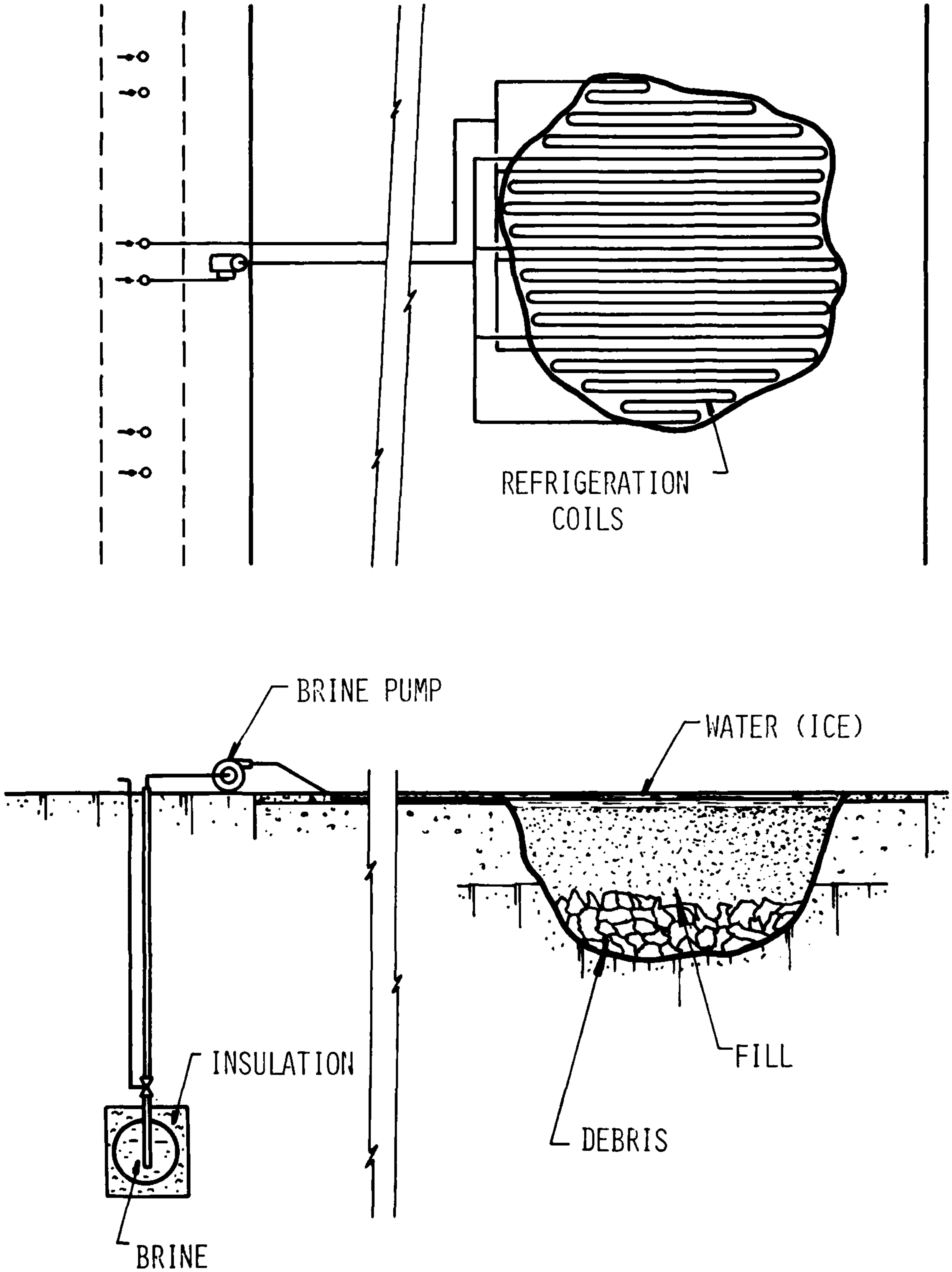


Figure 33. Concept No. 11

of the original surface. A polyethylene membrane should then be placed on the fill material. and preformed sections of refrigeration tubes should be placed in the cavity above the membrane.

A brine pump should be connected to the cold brine reservoir buried on either side of the runway at a sufficient depth so that it will not be damaged during the bombing. The refrigeration coils located in the top of the crater are connected to the brine pump through flat tubes laying on the runway. The maximum thickness of the tubes laying on the runway should be 1/2 inch or less.

While the brine lines are being connected, the area above the membrane should be filled with water and the brine pump should be turned on to start circulating the 20°F brine. This process is the same as that used to create an ice rink. It would require approximately 230 tons of refrigeration to freeze a 70-foot-diameter, 6-inch-thick pond in 20 minutes. With a sufficiently large reservoir of refrigerated brine, this could be accomplished within the time specified.

PRIMARY MATERIALS

- Sand and graded aggregate fill
- Polyethylene membrane
- Refrigeration coils

Weight of Material Required to Fill a Volume of 150 Yd^3

- 200 tons of sand and/or aggregate
- 12,000 ft of 3/4-inch-diameter refrigeration tubing
- 15,000 gallons of water

Cost

- High

Advantages

- Simple to install (same as ice rinks)
- Standard equipment
- Long shelf life
- Refrigeration system could be used to cool building as standard practice

Disadvantages

- Large portable refrigeration pumps required (total of 15,000 gal/min required at each large crater)
- May not be as useful with repair of small craters

- Large refrigeration unit required to maintain system at desired capacity

- High heat transfer rates required

Major Equipment Required

- Refrigeration unit, 500 tons

- Large portable refrigeration pumps

- Several miles of tubing

Additional Research and Development Required

- Evaluation of ability to meet one hour response time; probability of success - moderate

m. Concept 12. Explosively Driven Fill System (See Figure 34.)

Procedure - This concept involves the rapid displacement of fill material from storage areas adjacent to the runway to the crater with the use of explosives and deflection plates. The explosives would be used to drive the fill material, and a deflector shield would be used to direct the path of travel.

It is anticipated that earth-moving equipment would have to be used to push some of the fill material that lands on the runway adjacent to the crater into position; however, with proper positioning of the deflector plates and correct size of explosive, most of the fill material should land in the crater. Because of the rapid filling of the crater with this method, some compaction or other stabilization technique would have to be utilized so that the fill would support the aircraft loads.

The cap used with this repair procedure should be either a quick setting inorganic or organic binder.

PRIMARY MATERIALS

- Explosives

- Graded aggregate

Weight of Material Required to Fill a Volume of 150 Yd^3

- Approximately 750 lb of explosive

- Deflector shield

- 250 tons of fill material

Cost

- Low

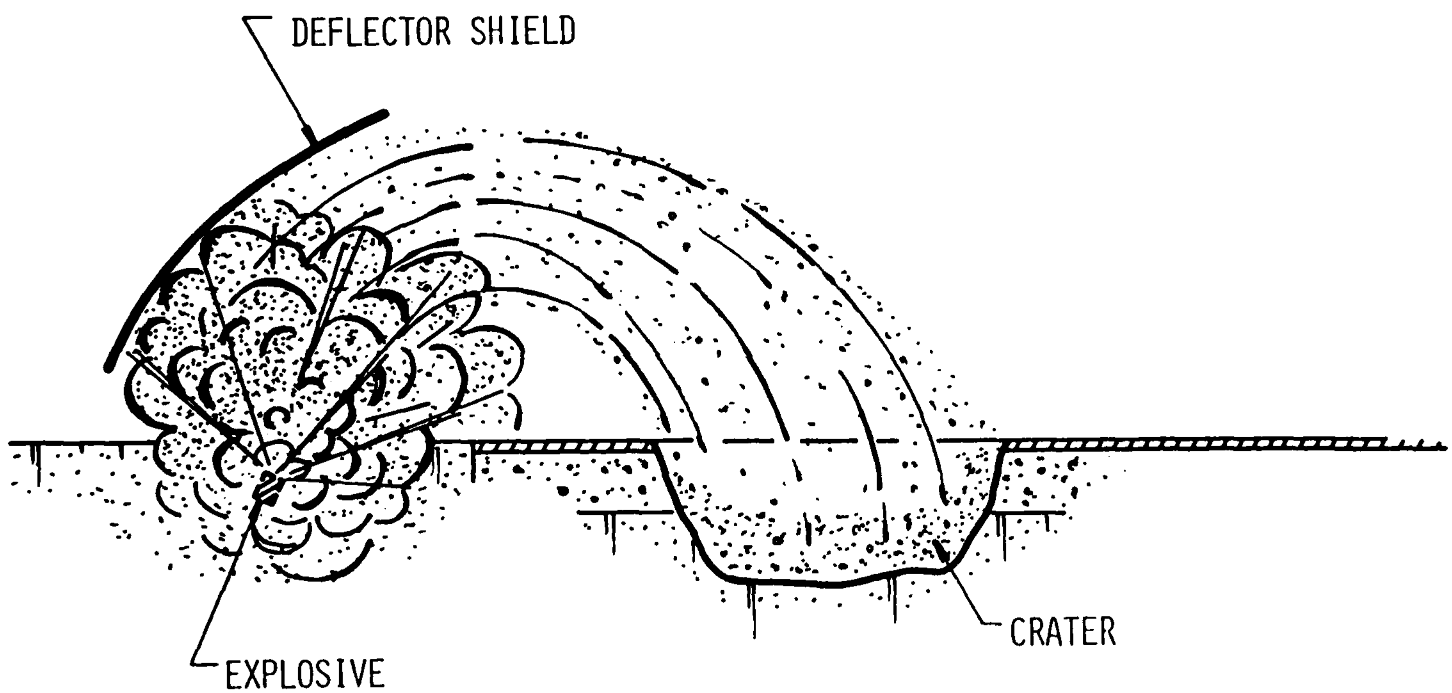


Figure 34. Concept 12

Advantages

- Very rapid transportation of fill material

Disadvantages

- Compaction required
- Only EOD trained personnel can set charges
- Limited control of direction of debris

Major Equipment Required

- Explosives
- Deflector shield

Additional Research and Development Required

- Evaluation of procedure to determine feasibility; probability of success - low

2. Concept Evaluation

The twelve concepts which are described in the preceding subsection survived the initial screening process because each one had at least one desirable characteristic. It is important to recognize that there are innumerable combinations of materials and repair processes which did not survive the initial screening process which was continually in practice during the concept development work. Also, as part of the concept formulation work, the research team aggregated similar repair techniques into a family of similar repair processes. These families of repair processes were then treated as a single concept. A concept in this context is defined as a generalized solution to the problem of expeditious runway repair which uses similar materials, equipment, or processes.

Twenty-two specific repair procedures were evaluated by the project team. These 22 procedures were grouped into the 12 concepts previously described. For the purposes of the evaluation, shreadouts of the 12 basic concepts were included so that the project team had the opportunity to review each one separately. In this application an alphabetical designator is used to identify a concept shreadout.

a. Evaluation Criteria

In an attempt to assess the merit of each of the 12 concepts, six criteria were selected for scoring each concept. The six criteria are listed in Table 5.

During the course of the analytical work, from which these six criteria were developed, it was apparent that each criteria must have a weight which reflects its relative contribution to the evaluation. The scoring criteria and the point spread for each criteria is shown in Table 5.

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NEW CONCEPT STUDY FOR REPAIR OF BOMB-DAMAGED RUNWAYS. VOLUME I.--ETC(U)
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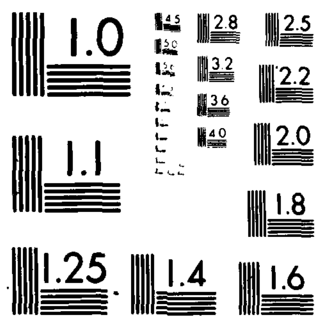


MICROCOPY RESOLUTION TEST CHART

TABLE 5. EVALUATION CRITERIA FOR RANKING RUNWAY REPAIR CONCEPTS

CRITERIA	SCORE (POINTS)
1. Ability to produce a serviceable runway within 1 hour	10 < 1 hr 1 hr < 9-1 < 4 hr 0 > 4 hr
2. Amount of additional R&D required	7 = None 0 = Great deal with low probability of success
3. Performance of system in adverse environmental conditions	7 = Unaffected 0 = Unusable under many conditions
4. Cost	4 <$100K/large crater 3-2 < $100K-$500K/ large crater 1 < $500K/large crater
5. Safety	4 = Very safe 0 = Very dangerous
6. Simplicity	4 = Very simple 0 = Complicated

b. Evaluation Process

The 12 concepts were independently evaluated using the criteria and the point spread in Table 5 by each of six technical specialists at the contractor facility who participated in the program. The quantitative results of that evalution process are provided in Table 6. The score represents the arithmetic mean of the scores for each concept.

C. Evaluation In Summary

It is apparent from the review of the quantitative data in Table 6 that Concept 2 using wet sand was a singular first choice with the project team followed by three equally ranked second choices.

3. Spall (Scab) Repair

Strafing raids have often accompanied bombing missions. As a result of the strafing, hundreds and sometimes thousands of very small craters or spall areas have to be repaired before a runway is operational. Most of the techniques discussed in Section II, paragraph C.1, are not applicable for the repair of the spall area which may be only 3 to 6 inches deep and 1 foot in diameter. Therefore, it is suggested that the Air Force consider building a spall repair vehicle designed specifically to repair very small craters. Figure 35 illustrates the basic components required.

There should be two rotating debris removal brushes located on the front of the vehicle. The lead brush should have long, flexible bristles capable of removing debris from the bottom of the spalls. The second brush should have stiff bristles capable of removing the rock and debris from the area adjacent to the spall.

The truck should be capable of carrying about 5000 lb of repair materials. These materials should be a two-component mix which is easily blended, is fluid and molds easily prior to its gel state, cures rapidly, and develops an excellent bond with old concrete or asphalt. There are several inorganic and organic cements that have these characteristics.

In operation, the vehicle would travel over the spall zone clearing the loose debris. The operator would automatically transfer the base materials, in the proper ratios, to the blender. The mix would be discharged from the blender through a line to the front of the screed bar. The fluid mix would fill the spall, and the screed bar would smooth the surface of the repair. The operator should have control of the rate of mix and discharge of the blended materials since the pot life of the proposed repair material should be 15 minutes or less. Therefore, only enough material to fill a few spalls should be in front of the screed bar at any given time.

4. Alternate Strip Repair

a. Introduction

An alternative to immediately repairing the main runway would be to use an alternate strip to launch and recover aircraft. The alternate strip could be constructed before the attack and be located a reasonable distance away from the main runway so that it would not be accidentally damaged in the raid on the main runway. In this way, the alternate strip

TABLE 6. MAIN RUNWAY BOMB DAMAGE REPAIR CONCEPT EVALUATION

RANK	SCORE[a]	CONCEPT	
		NUMBER	DESCRIPTION
1	31	2	Wet sand fill
2	27	1a	Cement slurry + inorganic fill
		4a	Fiberglass mat over cement
		4b	Fiberglass mat over sand
3	25	6a	Expanded organic fill + inorganic binder
4	24	3a	Cereal bowl (inorganic)
5	23	5a	Fill + fabric membrane + inorganic cap
		6c	Expanded inorganic fill + inorganic binder
		7a	Liquid filled bags + inorganic binder and cap
		8a	Sand bags + inorganic binder and cap
6	22	10a	Debris + fill + aluminum deck
		10b	Debris + fill + steel or fiberglass deck
7	21	11	Ice + wet sand
8	20	6d	Expanded inorganic fill + organic binder
9	19	8b	Sand bags + organic binder and cap
		9	Foam in place + inorganic cap
10	18	6b	Expanded organic fill + organic binder
		7b	Liquid filled bags + organic binder and cap
11	15	1b	Polymer cement slurry + fill
		3b	Cereal bowl (organic)
		5b	Fill + fabric membrane + organic cap
12	14	12	Explosive fill

NOTE: (a) Maximum possible score = 36
Source: Southwest Research Institute

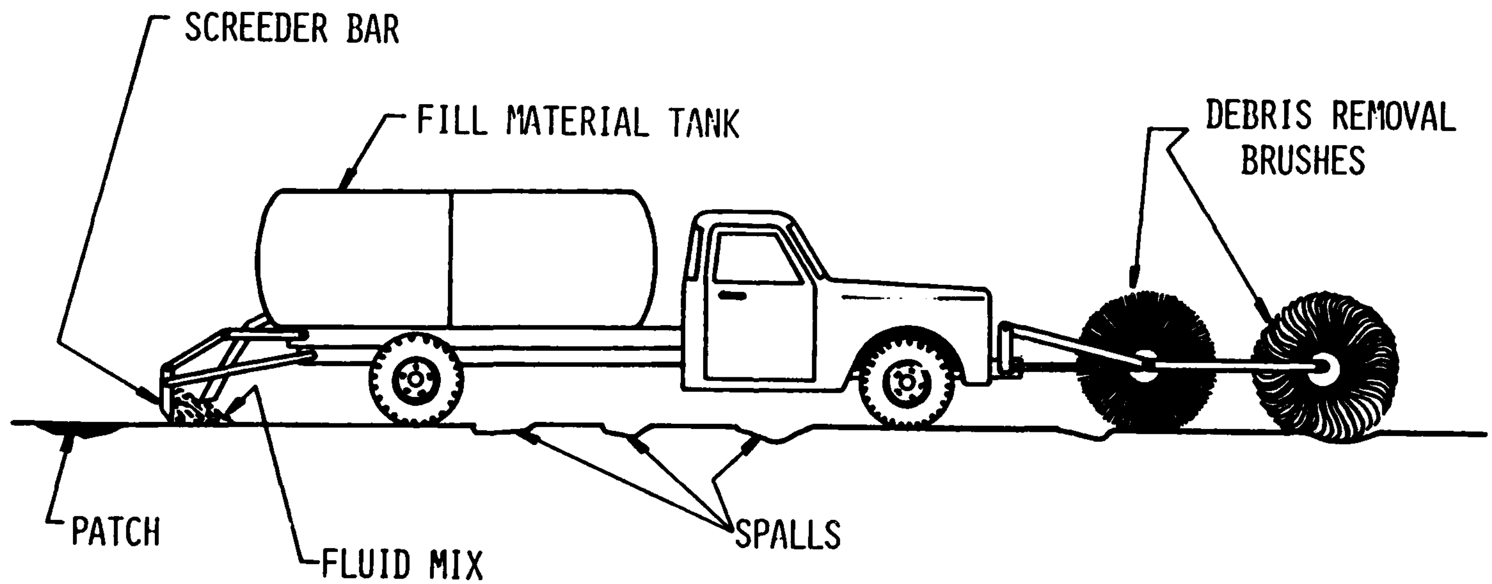


Figure 35. Truck-Mounted Spall Repair Concept

would have to be a secondary target for the enemy and thus dilute the effectiveness of the attack on the main runway.

Another alternative would be to rapidly construct an alternate strip that could be used a short time after the raid is over. Both of these procedures were considered during this phase of the project.

There are a number of considerations that must be taken into account when selecting a location for an alternate strip at an existing air base. These include the following:

- The strip should not contain primary or secondary aim points of existing potential targets.
- The strip should be at least 500 feet away from the main runway or another primary aim point.
- The strip should be directed into the prevailing winds.
- The strip should be located within the airfield boundary for security and logistic reasons.
- The strip should, however, be located away from the airfield complex.

If the alternate strip is going to be constructed prior to the attack, some additional construction considerations should also be taken into account. These are the following:

- The location of the strip will probably be known to the enemy; therefore, it will be targeted and hit during the raid. For this reason the alternate strip should be constructed so that it can be easily repaired (i.e., if no cap is put on the alternate strip, it will be easier to repair because no upheaval will have to be removed).
- The strip should be designed for a short, finite operational life.
- The strip should be designed for prevailing climatic conditions (i.e., aggregate and sand instead of aggregate and clay for European climates).

Figure 36 illustrates a typical layout for an air base with the addition of an unpaved alternate runway that parallels the main runway and two potential sites where 5000 feet long rapidly constructed runways could be built. All three alternate strips could be reached by the aircraft using existing taxiways. As indicated in Figure 36, the area adjacent to the main runway and taxi strips could be stabilized or covered with an aggregate base to accelerate rapid repair of potential alternate strips after an attack.

b. <u>Alternate Runway Rapid Construction Technique</u>

One approach to preparing an alternate strip would be to actually construct a temporary runway strip to launch and recover aircraft while more permanent repairs are being made to the main runway.

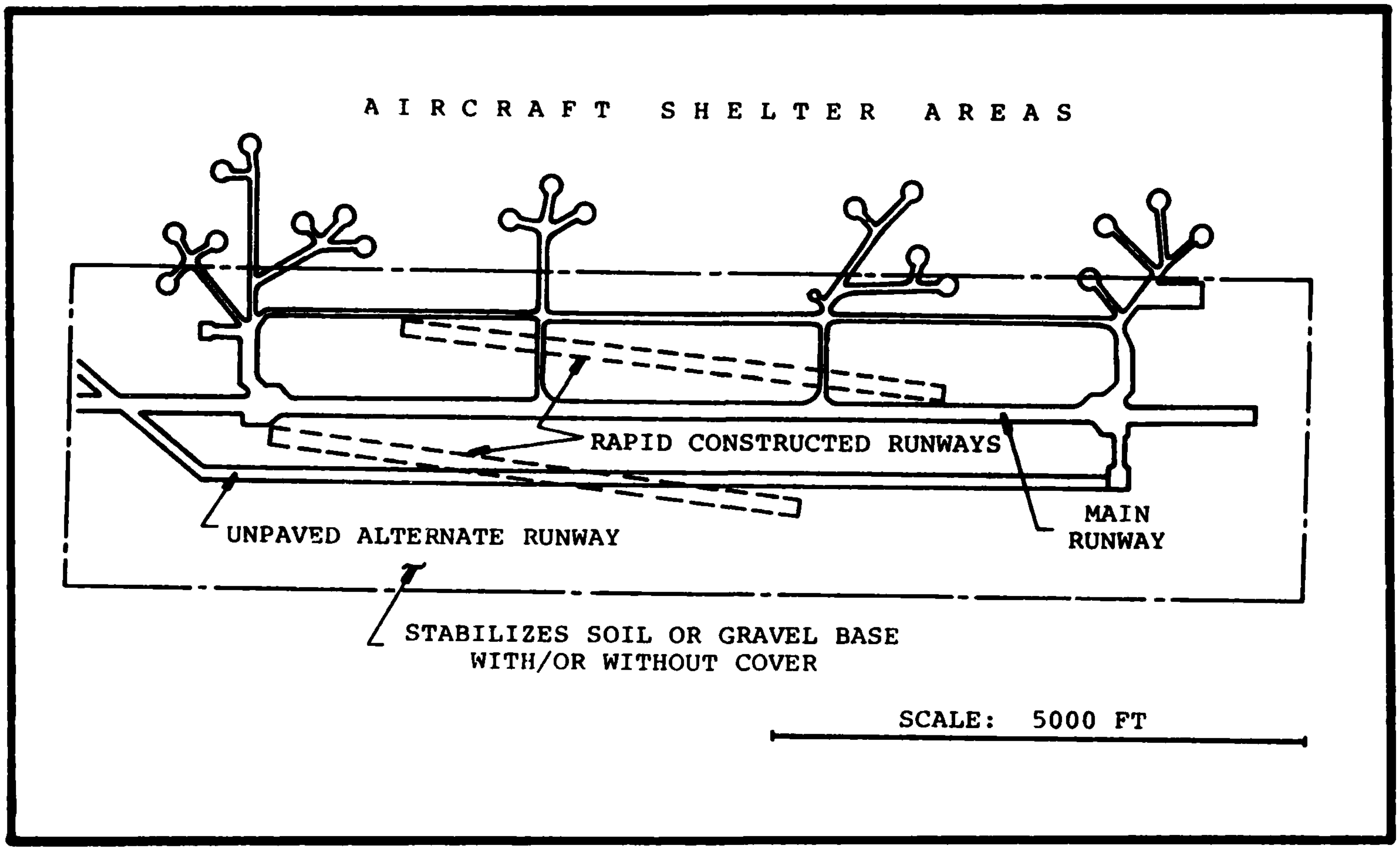


Figure 36. Typical Airfield Layout With Unpaved Alternate Runways

This could be done by using a system similar to the one illustrated in Figure 37. In this system a set of bulldozers would clear a path at least 50 feet wide and 5000 feet long. The tow vehicles would be positioned behind the bulldozers. Spacer bars would be attached to the two lead vehicles to maintain the distance between the trucks. Then a 50 feet wide by 5000 feet long roll of 1/8-inch-thick fiberglass mat would be connected to the rear of the lead vehicles. Two polymer spray bars would then be connected to the back of the tow vehicle and positioned ahead of and behind the roll of fiberglass mat. The spray bar would then be connected to the mixing pump and polymer storage tanks located on the tow vehicle.

Next the second set of tow vehicles would be positioned behind and attached to the lead vehicle. Again, a fiberglass mat roll would be attached to the truck and the spray bar connected to the polymer mixing unit. The spacing between the trucks would be maintained using spacer bars.

A set of tow vehicles is required for each ply of fiberglass/polymer. As many plys as necessary could be applied with a single pass of the system. Sand could be applied to the surface of the last ply to obtain the proper coefficient of friction. Each ply would be between 3/16 and 1/4 inch thick. With a good stable sub-base, 3 to 5 plys should be sufficient to support aircraft loads for at least several hundred passes.

MATERIAL REQUIRED

- Fiberglass mats (woven roving)
- Polymer (polyester resin and catalyst or initiator)

Amount of Material Required

- 250,000 ft^2 of fiberglass mat/ply
- 20,000 gallons of polymer/ply

Cost

- High

Advantages

- Rapid installation on alternate strip
- Could be constructed in undamaged area after raid
- Easily repaired

Disadvantages

- Very expensive
- Short shelf life polymers requiring frequent resupply
- Ultimate support depends on site preparation prior to attack

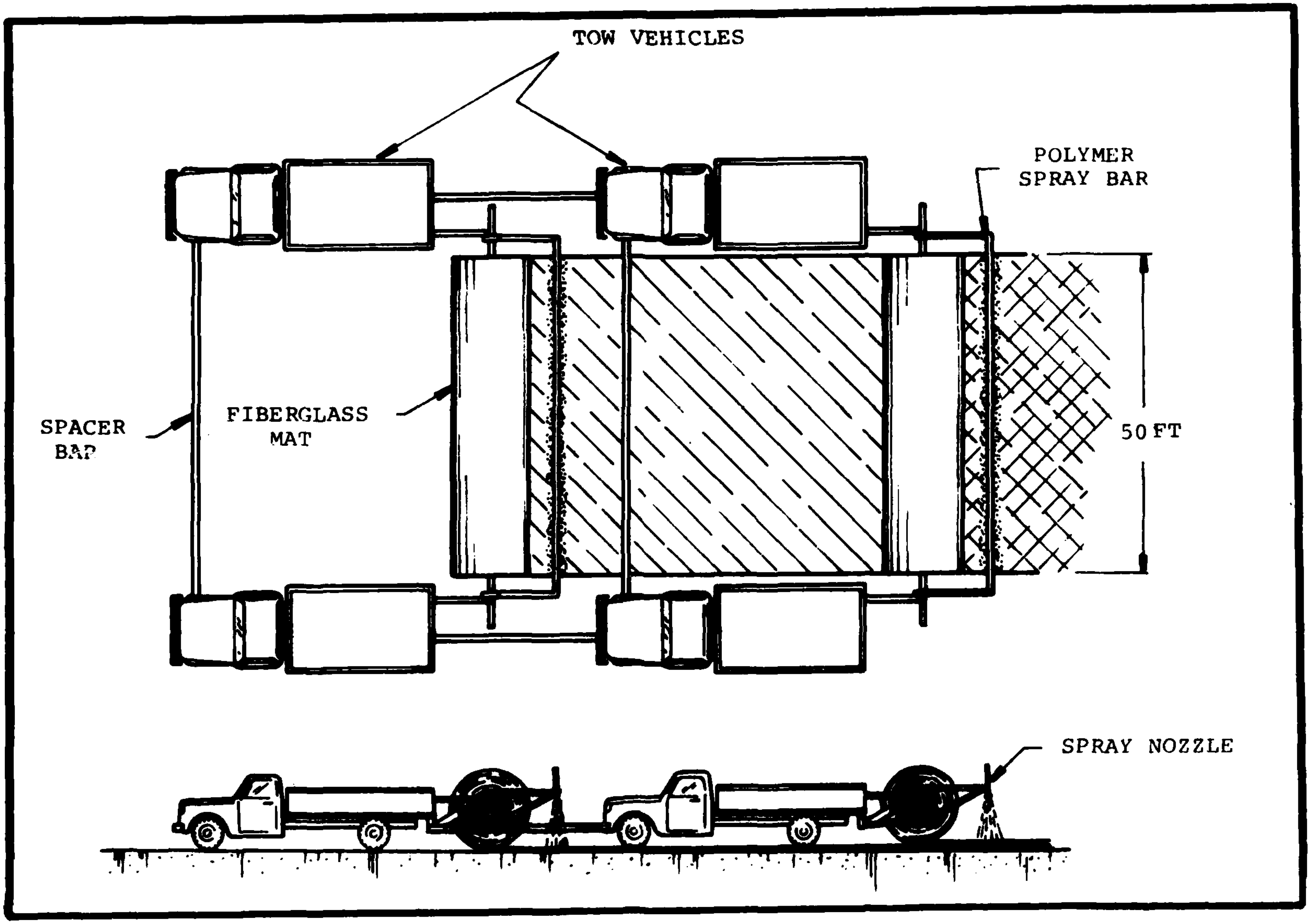


Figure 37. Alternate Runway Construction Using Fiberglass-Reinforced Polymer Mat

Major Equipment Required

- Tow Vehicle System

Additional Research and Development Required

- Tandom tow vehicle system; probability of success-high
- Ability to handle large rolls of fiberglass in field; probability of success - moderate
- Design of rapid mixing and spray system; probability of success - moderate
- Evaluation of system to support aircraft loads; probability of success - moderate

c. Protection of Alternate Strip

If an alternate strip is constructed before the attack, it may be possible to protect it from damage. In order to accomplish this, the protection technique must counter one or more elements in the function train of events. These include:

- Target Acquisition - prevent target acquisition by camouflaging the alternate strip
- Impact - avoid direct contact of the alternate strip surface
- Fuze Function - defeat the fuze in some manner
- Penetration - by a hardened surface
- Explosive Initiation - detonate the bomb above the surface of the strip

1. Alternate strip covers

Several systems were considered that would cover an alternate strip and initiate weapons before they impacted the strip. Shown in Figures 38, 39, and 40 are a lightweight arch, deck, and net systems. In all cases the aircraft would have to be launched and landed under these covers, which raises major objections by the users of the system. In addition, any damage done to either the arch or the deck systems as a result of the air raid would have to be cleared before the strip could be used. The net would be easiest to repair and use; however, it may still have a low user acceptance rating.

MATERIAL REQUIRED

- Lightweight arch, or
- Lightweight deck, or
- Lightweight net

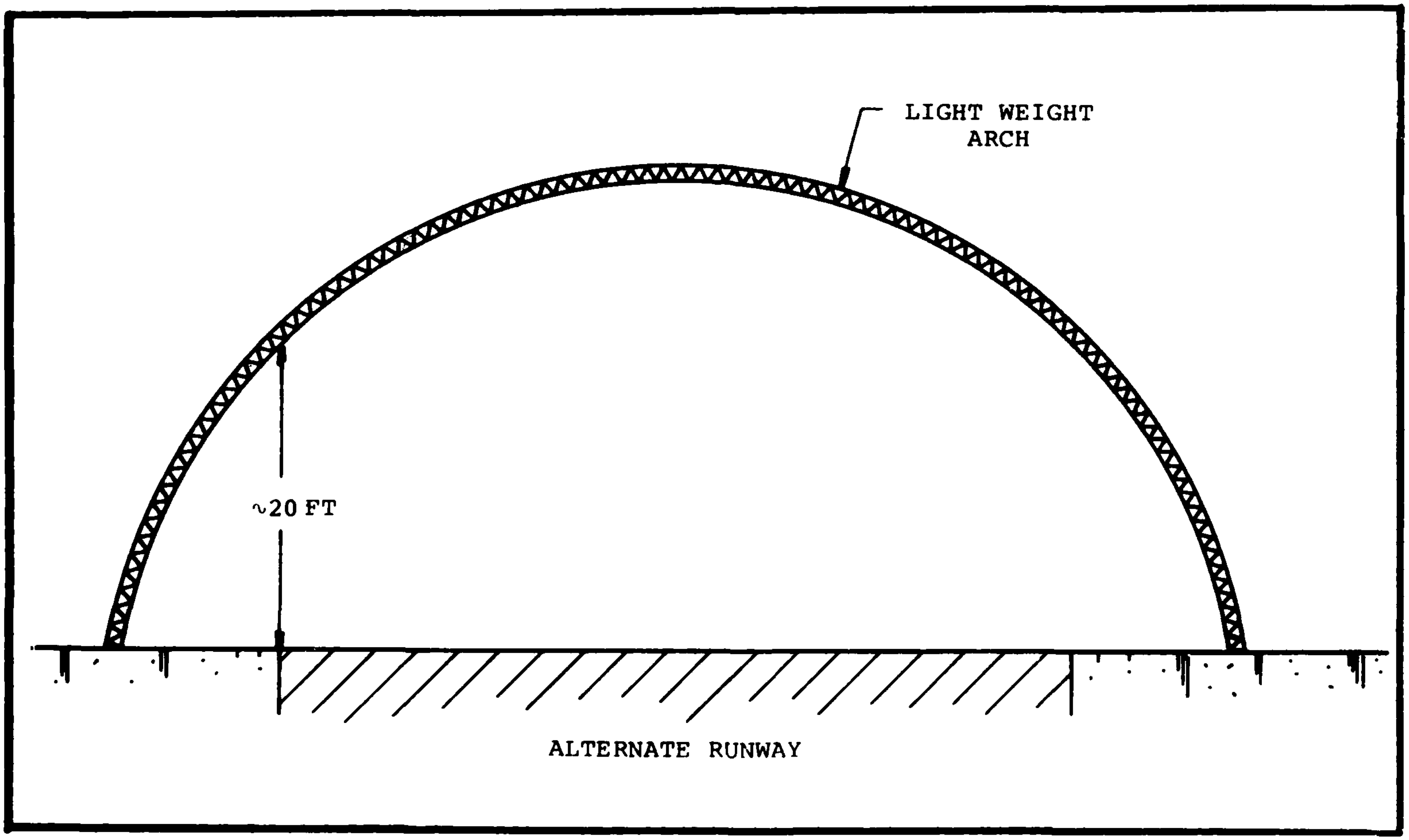


Figure 38. Alternate Runway Concept Using A Lightweight Arch For Cover

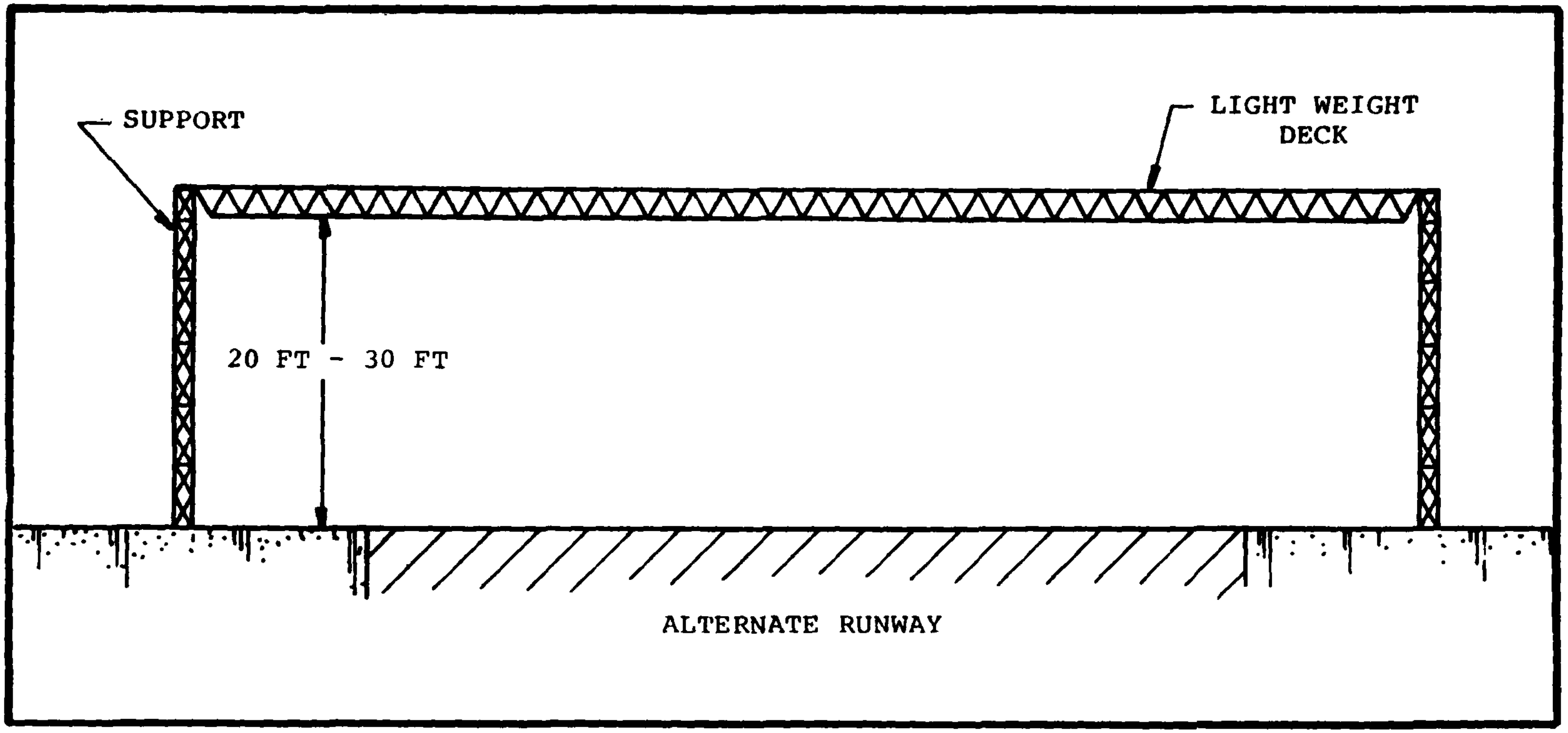


Figure 39. Alternate Runway Concept Using Lightweight Deck for Cover

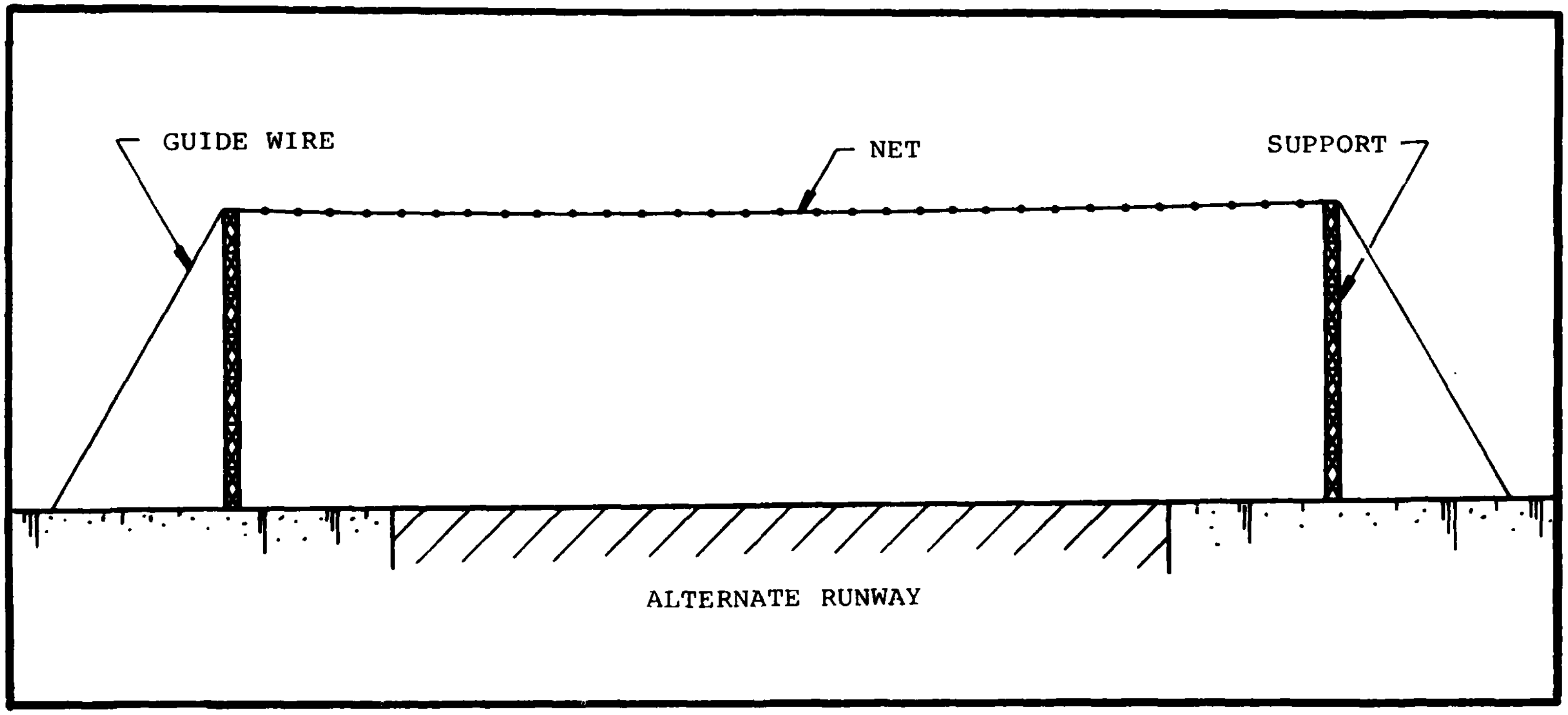


Figure 40. Alternate Runway Concept Using Net for Cover

Amount of Material Required

- At least 350,000 ft^2 of cover material plus support system

Cost

- High

Advantages

- Will prevent significant damage to alternate strip

Disadvantages

- Will be difficult to launch and recover aircraft under cover
- May have low user acceptance
- Expensive to build
- Damage to structure will have to be removed before strip would be functional

Additional Research and Development Required

- Ability of system to defeat weapon systems; probability of success - moderate
- Ability to launch and recover aircraft under cover; probability of success - moderate

2. Water reservoir alternate strip

Another system that was considered as a protected alternate strip system involved the use of a water reservoir adjacent to the main runway. Such a system is illustrated in Figure 41. The bottom of the reservoir could be used as an alternate runway after the water was drained. The water could be drained rapidly through a specially designed set of large lines.

The reservoir would be deep enough so that delayed weapons could explode before they contacted the bottom and thus minimize the damage done to the alternate strip surface. The duds, mines, and long term delay weapons that would come to rest on the bottom of the reservoir might be swept out of the reservoir when the drainage gates are opened. The rate of drainage should be such that the reservoir would be emptied within 20 minutes of opening the valves.

MATERIAL REQUIRED

- Concrete-lined water reservoir

Amount of Material Required

- 6×10^6 gallons of water

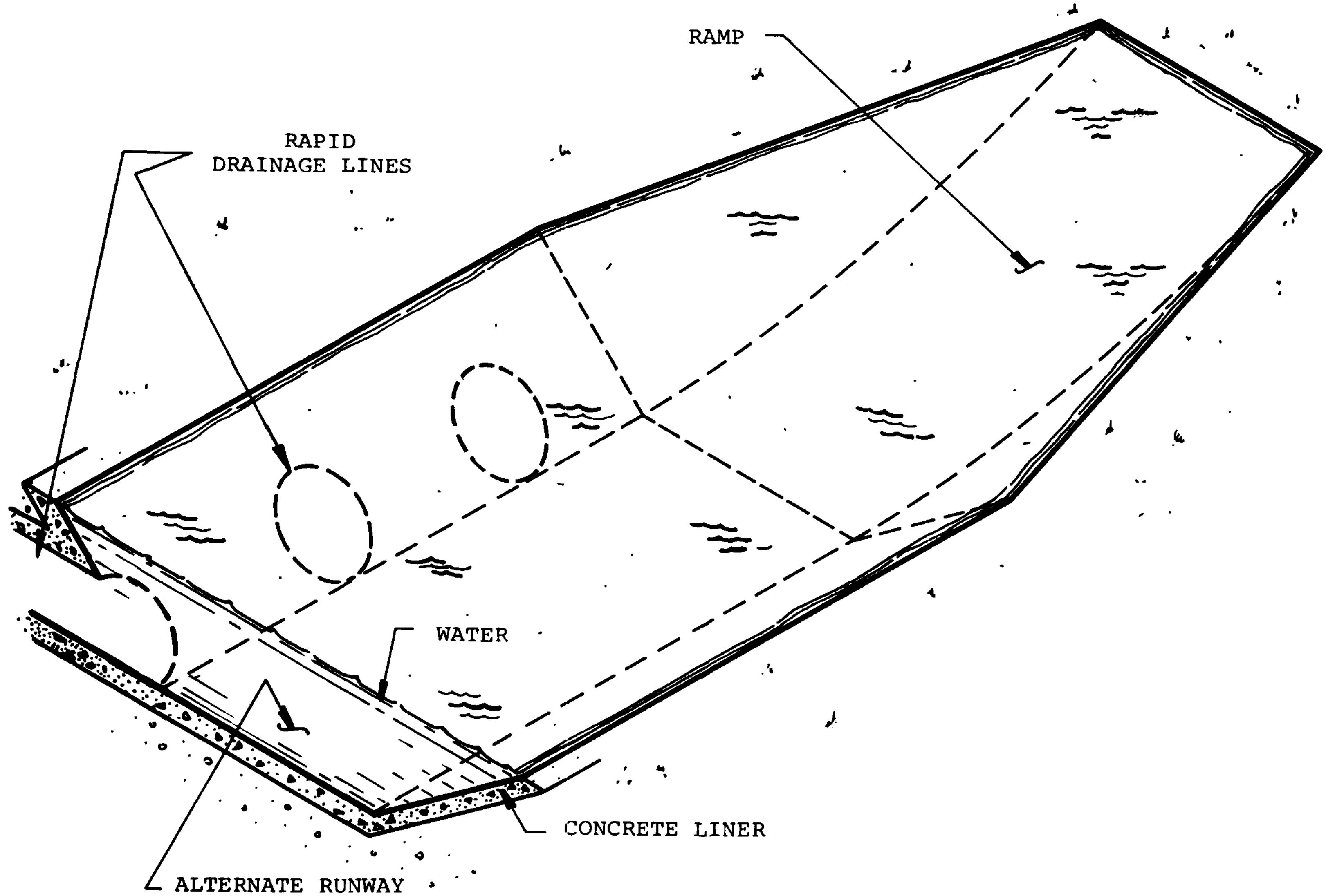


Figure 41. Illustration of Alternate Runway Concept Using Flat Bottom Water Reservoir

Cost

- High

Advantages

- Will protect alternate strip from damage
- Could be used for storm drainage during peace time

Disadvantages

- Water discharge may cause flooding downstream
- High cost installation

Additional Research and Development Required

- Ability of water reservoir to defeat weapon system; probability of success - moderate
- Ability to drain reservoir and make system operational within 1 hour; probability of success - high

3. Massive cart system

Another approach to protecting an alternate runway would be to cover it with a massive amount of soil or aggregate that could be removed rapidly. A system of this nature is illustrated in Figure 42. The soil or aggregate would be placed on large mobile carts that could be moved after the attack. The depth of material on the cart would be sufficient to absorb the explosive force of a direct hit and still allow the carts to be moved.

Each cart would have side walls so that the aggregate or soil would not spill during the moving operation and thus interfere with the movement of the adjacent carts. In the event that the adjacent walls of two carts are damaged during the attack, the two carts could be moved together.

MATERIALS REQUIRED

- Large mobile carts
- Soil or aggregate

Amount of Material Required

- 500 mobile carts
- 140,000 yd^3 of soil or aggregate

Cost

- High

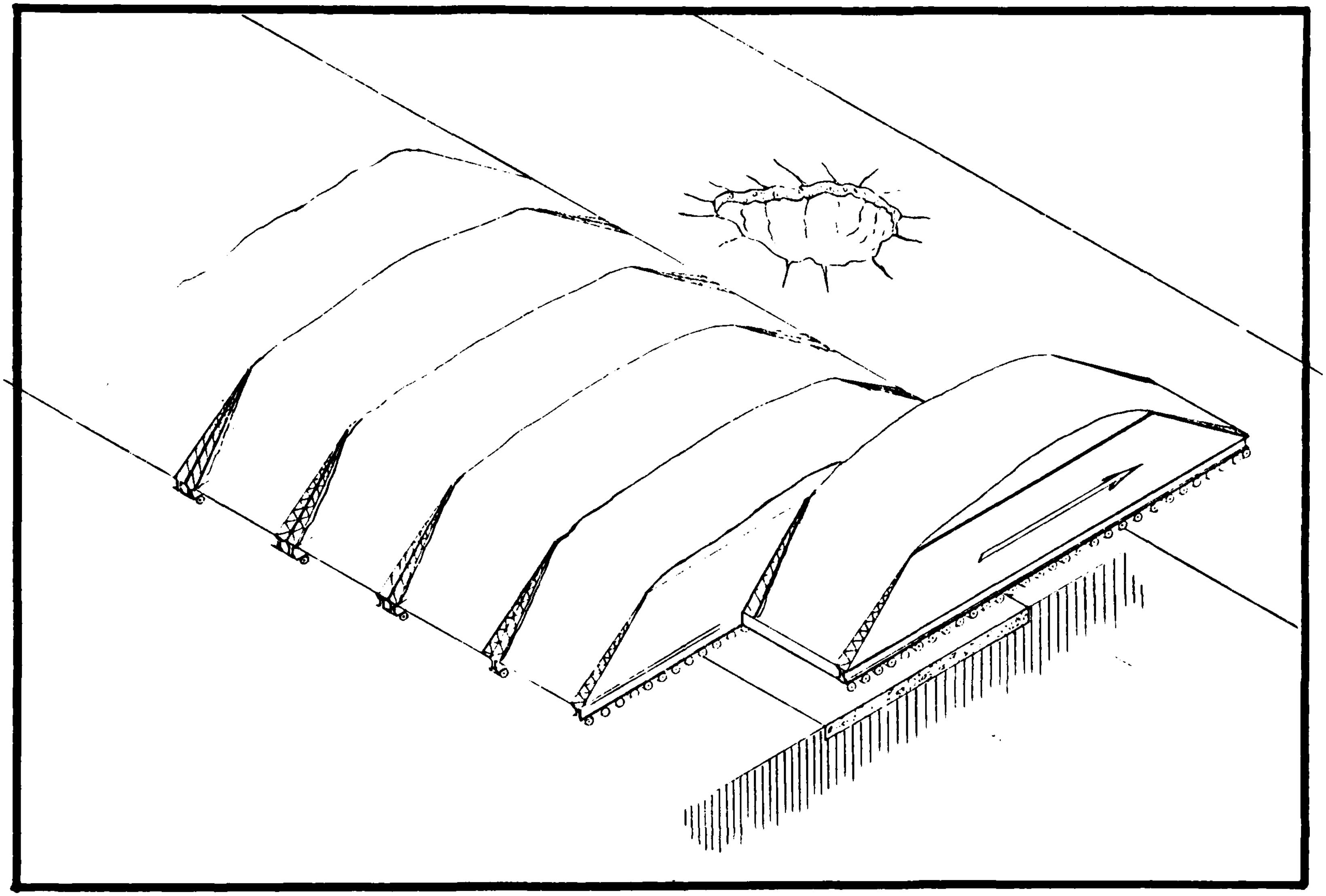


Figure 42. Alternate Runway Concept Using Massive Amounts of Soil on Carts

Advantages

- High probability of protecting alternate strip

Disadvantages

- Large masses to be moved in short time
- Movement of damaged carts may be a problem

Additional Research and Development Required

- Ability to move large carts; probability of success - high
- Effectiveness of massive carts in protecting alternate strip; probability of success - moderate

d. Unprotected Strip

An unprotected alternate runway, constructed parallel to the main runway and prior to the attack would probably receive some damage during the action. If the alternate runway is properly designed, it may be easier to repair than the main runway. It is important that the designers of the alternate runway take into consideration the fact that it is, in reality, an emergency runway that should have a finite short useful life. Therefore, it should be designed to support the critical aircraft for a limited number of takeoffs and landings.

It is recommended that well graded sand and aggregate be used as a sub-base. The basis for this recommendation is that the sand and small aggregate will be self-compacting when wet with water. In addition, the aggregate can be successfully used as the runway surface for the alternate strip. Presently, aggregate runways are being used for commercial jet aircraft (B727 and B737) in Alaska. On some aircraft small fenders or rock deflectors may have to be added in order to avoid FOD to the aircraft. If it is decided that a cap has to be placed on the alternate strip, it should be as thin as possible (< 2 inches thick) to minimize the amount of upheaval.

The repair materials (sand and aggregate) should be stored adjacent to the alternate runway so that the amount of time required to haul the materials to the repair site is minimized. The amount of material that will have to be added to the repair should be very small, since all of the debris that is blown out of the crater should be available for backfill.

As indicated earlier in the report, the size of the equipment used to repair the damage has an inverse relationship to the amount of time required to repair a crater and a direct relationship to the cost of the equipment. Therefore, a reasonable trade-off between size, response time, and cost has to be made when selecting equipment for any RRR operation. Two time event charts for the repair of ten 25-lb bomb craters and one 750-lb bomb crater are shown in Figures 43 and 44, respectively. For the total repair, three sets of the equipment mix indicated in the charts would be required.

MATERIAL REQUIRED

- Well graded sand and aggregate

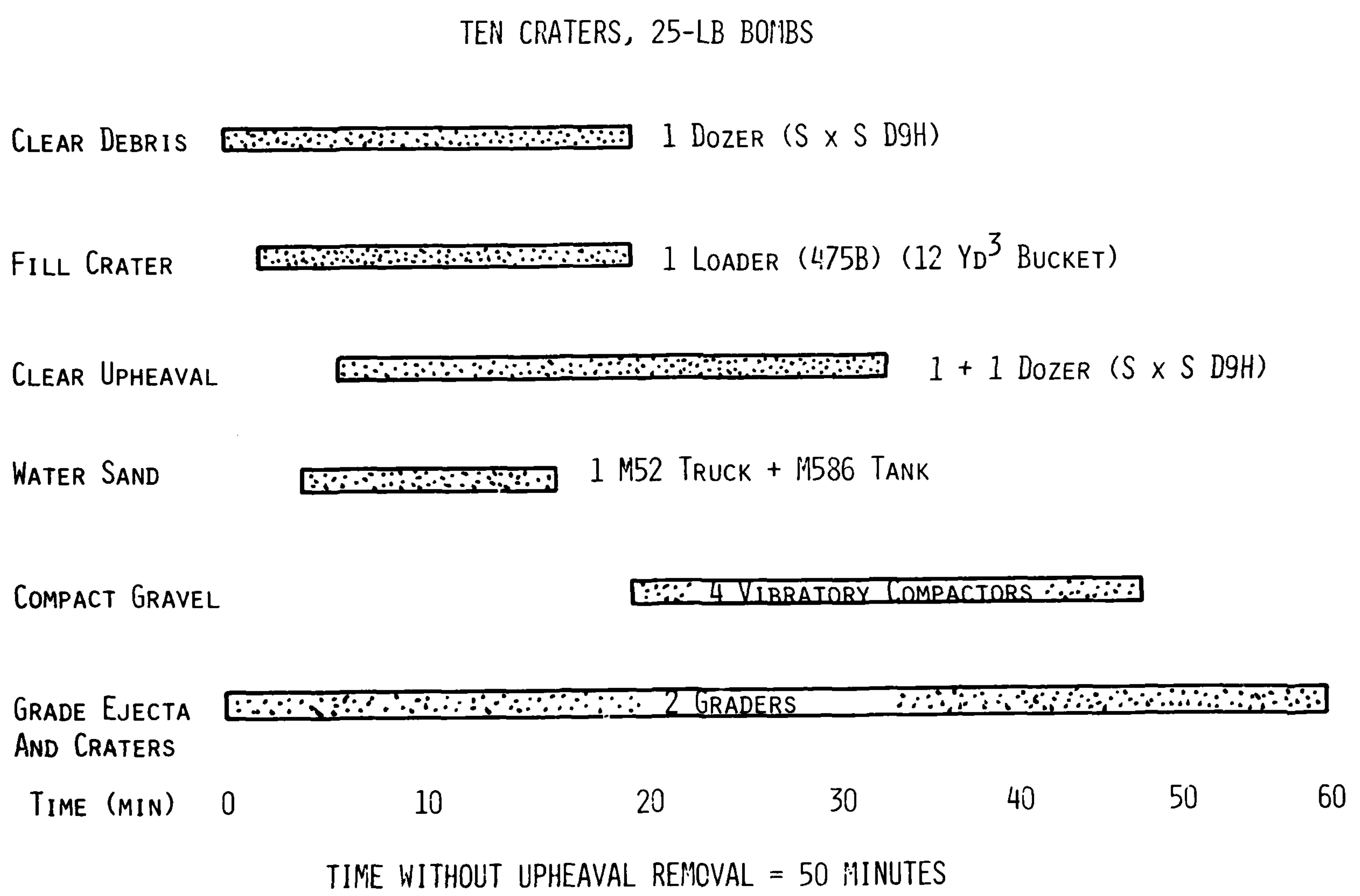


Figure 43. Event Chart for Repair of Ten 25-Pound Bomb Craters

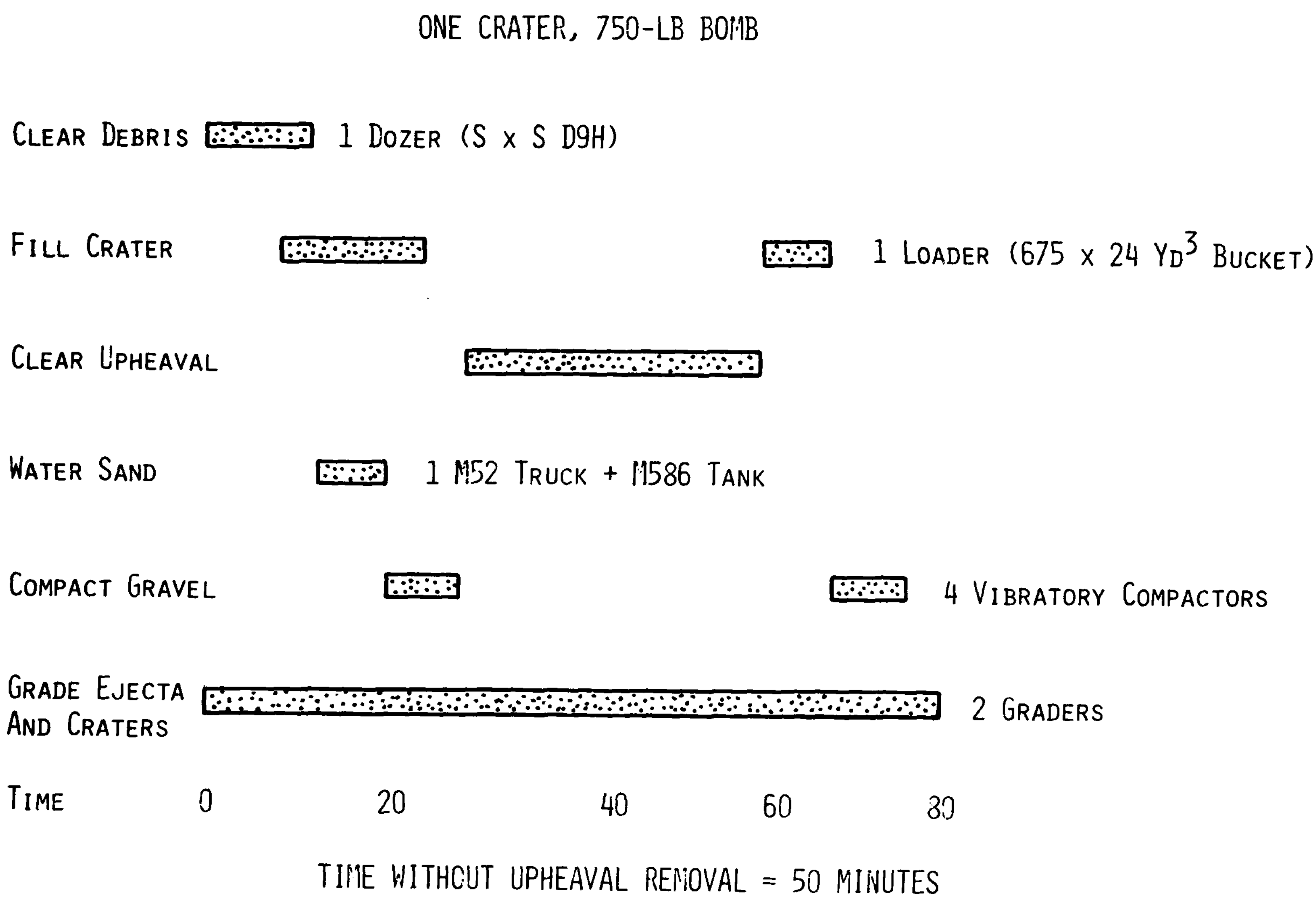


Figure 44. Event Chart for Repair of One 750-Pound Bomb Crater

Amount Required to Fill a Volume of 150 Yd^3

- 100 tons (without rigid cap)

Cost

- Low (if initial cost of alternate strip is not included)

Advantages

- Easily repaired
- Can be repaired in approximately 60 minutes
- The alternate strip would dilute attack on main runway

Disadvantages

- Aggregate landing surface may not be received well by flight crews
- May require some slight modification to landing gear to avoid FOD

Additional Research and Development Required

- Compare effects of bomb damage on paved and unpaved strips; probability of success - high
- Test ability to launch and recover Air Force planes from unpaved strip; probability of success - high

SECTION III

CONCLUSIONS AND RECOMMENDATIONS

The work conducted during this project was predominantly exploratory in nature, the principal result of which is repair scenarios and descriptions of repair concepts described in uniform styling for comparative analysis. The evaluation of the concepts was directed at narrowing and focusing the scope of the subsequent planned work.

The conclusions and recommendations which can be made from this exploratory work are limited to generalizations about the basic factors involved in repair of runways during combat conditions. The basic factors considered in this study are damage assessment, equipment, materials, and repair processes.

The problem of explosive ordnance disposal has been treated as a related yet separate problem. The results of the EOD study undertaken as part of this program were submitted to the sponsor and will not be incorporated in a published report. The conclusions of this brief study indicate that a significant delay in the start of RRR operations could be encountered if mines and/or delay weapons are delivered to the airfield by the enemy.

A. Conclusions

1. Post-Attack Damage Assessment

The safest and most expeditious method of making the initial post-attack assessment of bomb damage is from an aircraft, preferably a helicopter. The results of this study and others indicate that the choice for the location of the repair operation is an extremely critical decision. The airborne location provides the best visual vantage point; however, this perspective must be supplemented with accurate bomb damage positioning techniques to chose the single best (least effort) repair strategy.

2. Equipment

Larger equipment will be required by the repair crews to significantly reduce the repair time. Loaders, trucks, and dozers are commercially available in sizes considerably larger than present base level inventory items. Current repair practices are constrained by equipment capacity; additional equipment units are not a viable option since work locations (work space) are very limited. Extra large units (such as those used with strip mining) are not suggested since they would find no application in routine base operations and minimal utilization.

3. Materials

There are several inorganic materials and several organic materials which have quick-setting characteristics which produce high strength repairs. All of the materials identified with these characteristics, however, have offsetting undesirable characteristics such as short shelf life, complex mixing and handling, and/or high cost. At this time there is no cap material which is clearly a first choice.

4. Material Handling

The best location for storage of materials which are used in high volume is adjacent to the runway, below grade in containers which provide protection from moisture. This approach reduces the requirement for material transport, equipment and personnel.

Any material which is quick-setting will require job site mixing, pumping, and surge storage. It is impractical to prepare materials at a remote location which have a pot life less than several hours since any delay at the job site would jeopardize the material transport vehicle.

5. Repair Process

Only materials and processes which can achieve full bearing strength without compaction should be considered because the time required to achieve desired bearing strength by means of compaction is significantly greater than the one-hour repair time objective.

Full period radio communication between the BDR officer and each BDR crew chief is required to achieve full utilization of personnel and equipment and to minimize interference between adjunct repair operations.

6. Alternate Runway

An alternate runway offers several strategic and operational advantages. An alternate runway constructed of stabilized base material would double the targets or halve the probability of runway damage. An alternate runway doubles the optimum repair locations and provides a work location for BDR crews after the initial repair is made to the least damaged recovery runway.

7. Overall Assessment

The probability of completing the repair of a bomb damaged runway within one hour with state-of-the-art materials and equipment is very low. However, reduction of the current 4-hour repair time by half to a 1-1/2- to 2-hour operation is feasible.

Signifcant reduction in repair time is possible using larger equipment, quick-setting material, and larger material handling equipment; however, these changes will require additional personnel capabilities and training.

B. Recommendations

The evaluation of the bomb damage repair concepts provided in this exploratory study were based upon criteria selected and used by analysts, engineers, and materials specialists. It is recommended that the results of this evaluation and the discussion conducted during the conference at Tyndall AFB, Florida, on 1 and 2 June 1978 be considered along with projected operational requirements, anticipated budgeting constraints, and manpower availability during the 1980's in the selection of three main runway repair concepts and one alternate runway repair procedure for detailed analysis during a subsequent evaluation phase of this program.

REFERENCES

1. Brooks, G. W., et al, Bomb Damage Repair (BDR) Damage Prediction, AFCEC-TR-75-24, October 1975.

2. Westine, P. S., Explosive Cratering, Journal of Terra-mechanics, 1970, Vol. 7, No. 2, Pergamon Press, Great Britain.

3. Concha, E. and Erickson, G., Bomb Damage Repair (BDR) Damaged Pavement Removal and Crater Backfill Equipment Study, AFCEC-TR-76-18, December 1976.

4. Hokanson, L. D., Tyndall AFB Bomb Damage Repair Field Test, Documentation and Analysis, AFWL-TR-74-226, October 1975.

5. Hokanson, L. D., Rollings, R. S., Field Test of Standard Bomb Damage Repair Techniques for Pavements, AFWL-TR-75-148, October 1975.

6. Brooks, G. W., et al, Bomb Damage Repair, Damage Prediction, AFCEC-TR-75-24, Volumes I and II, October 1975.

7. Caterpillar Performance Handbook, Edition 8, Caterpillar Tractor Co., October 1977.

APPENDIX A

RUNWAY DAMAGE ASSESSMENT PROCEDURES

RUNWAY DAMAGE ASSESSMENT (RDA) PROCEDURE NO. 1	HELICOPTER - LAUNCHED FOLLOWING ATTACK

Procedure

1. Assemble helicopter, team leader, crew, and equipment at hardened site.

2. Launch survey following attack.

3. Survey primary and secondary runways for:

   a. large bomb craters (750 lb)

   b. small bomb craters (25 lb)

   c. spalls (scabs)

   d. unexploded and delayed weapons

   e. mined areas.

   Note: Survey should be accomplished in four passes (2 each runway), altitude 75 to 150 feet, speed approximately 50 miles per hour. Total time required approximately 10 minutes.

4. Evaluate data recorded on survey map and select emergency runway location.

5. Mark emergency runway centerline and boundaries.

6. Mark taxiways and accesses to emergency runway.

Advantages

Fast $\leq$ 30 minutes.

Considers all factors - damage, mines, EOD, access.

Uses existing equipment.

Disadvantages

Helicopter subject to attack damage.

Requires well trained crew - observers, pilot, team leader.

Emergency runway selection largely subjective.

Expensive if the total cost of helicopter and its maintenance assigned to RRR operation.

RUNWAY DAMAGE ASSESSMENT (RDA) PROCEDURE NO. 2	HELICOPTER LAUNCHED BEFORE ATTACK

Procedure

1. Assemble helicopter, survey team, and equipment at earliest warning of pending attack.

2. Launch helicopter - proceed to location out of principal flight path of attacking aircraft where attack can be observed.

3. Observe attack, noting:

    a. bombing patterns

    b. types of ordnance

    c. mine/delayed bomb usage

4. Following attack, conduct survey of primary/secondary runways, noting:

    a. large bomb craters (750 lb)

    b. small bomb craters (25 lb)

    c. spalls (scabs)

    d. unexploded/delayed bomb locations

    e. mined areas.

5. Evaluate data and select location of emergency runway.

6. Mark centerline and boundaries.

7. Mark taxiways and other accesses to emergency runway.

Advantages

Fast $\leq$ 30 minutes.

Removes helicopter and crew from attack area at earliest possible time.

Considers all factors - damage, mines, EOD, access.

Uses existing equipment.

Disadvantages

Requires well trained crew - observers, pilot, leader.

Selection process largely subjective.

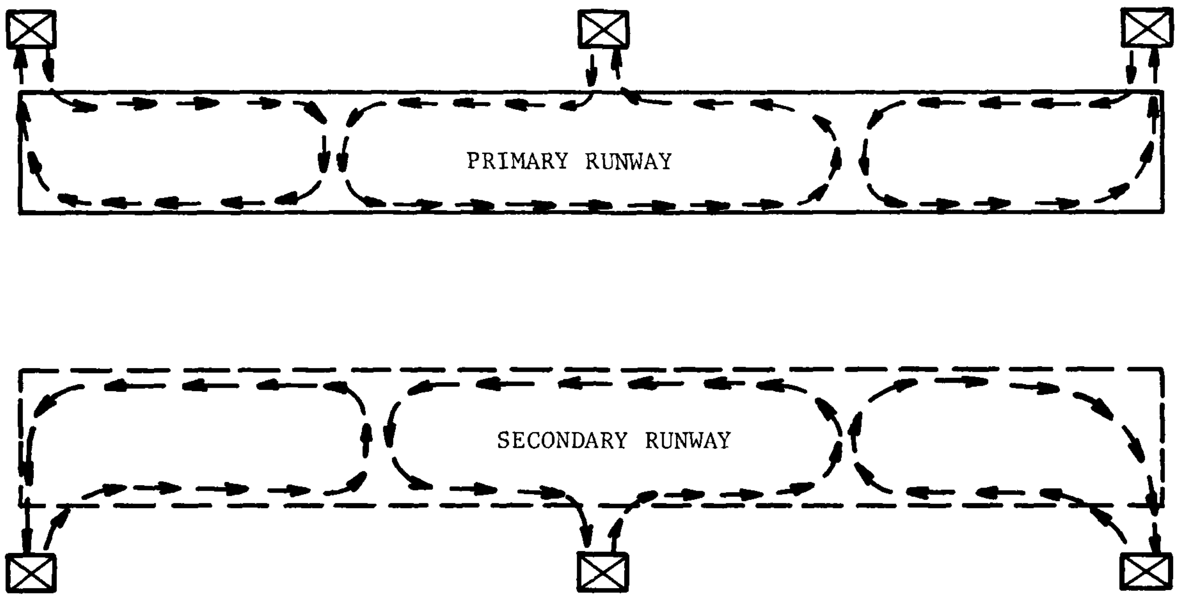
Hampered by darkness, adverse weather.

Expensive if the total cost of helicopter and its maintenance assigned to RRR operation.

RUNWAY DAMAGE ASSESSMENT (RDA) PROCEDURE NO. 3	GROUND SURVEY - JEEPS (1-6) WITH COMMUNICATION TO BASE COMMAND CENTER

Procedure

1. At time of alert, assemble jeeps and crews at selected hardened sites.



2. Upon "all clear" survey crews leave shelters and conduct survey per diagram above. All data on location of damage, types of ordnance used, mined crews, EOD, etc., is radioed directly to command center where it is plotted and analyzed by command personnel. Each team to complete survey in approximately 10 minutes (average speed approximately 6 mph).

3. Command personnel evaluate data and select site of emergency runway. Radio coordinates of emergency runway centerline and boundaries to nearest survey crews.

4. Survey crews dispatch and mark emergency runway.

5. Mark taxiways and other accesses to emergency runway.

Advantages

Responsive - $\leq$ 30 minutes.

Inexpensive - uses available equipment.

Survey crews need only minimal training.

Provides for command group decision on emergency runway location.

Disadvantages

Subjects survey crews to dangers of mines and delayed bombs.

Runway damage may preclude completion of survey by one or more teams.

Requires construction of hardened sites for crews.

Operations affected by weather, nighttime operations.

RUNWAY DAMAGE ASSESSMENT (RDA) PROCEDURE NO. 4	GROUND SURVEY - SINGLE JEEP WITH DECISION MAKER

Procedure

1. Single jeep with driver, observer and leader (decision maker) dispatched immediately upon "all clear".

2. Conduct survey of primary and secondary runway, noting:

   a. location and extent of bomb damage

   b. location and extent of strafing damage

   c. location and extent of mine and delayed bomb deployment.

3. Evaluate and determine location of emergency runway.

4. Mark runway and inform EOD, RRR and other teams of location.

Advantages

Extremely inexpensive.

Disadvantages

Extremely slow - requires minimum in excess of one hour.

Subjects survey team to dangers of mines and delayed ordnance.

Difficult to develop overall picture of type and extent of damage.

Places total responsibility and decision on survey team leader.

High probability of being unable to complete survey because of damage and/or mines.

Probably least efficient method available.

RUNWAY DAMAGE ASSESSMENT (RDA) PROCEDURE NO. 5	TELEVISION - HELICOPTER BASED

Procedure

1. Television-equipped helicopter launched before or immediately after attack.

2. Helicopter flys predetermined course and speed over primary and secondary runways. Video data is radioed to command post.

3. Incoming video data displayed on monitor and also subjected to computer analysis and display on appropriate plotting board.

4. Command personnel evaluate data and select emergency runway location - selection could be computer assisted.

5. Emergency runway coordinates radioed to RDA helicopter for marking.

Advantages

Fast - $\leq$ 30 minutes.

Provides extensive, accurate data.

Allows for command group selection of emergency runway location.

With appropriate lights and lenses, can be used in extreme lighting and weather conditions.

Disadvantages

Very expensive - requires extensive special equipment and development.

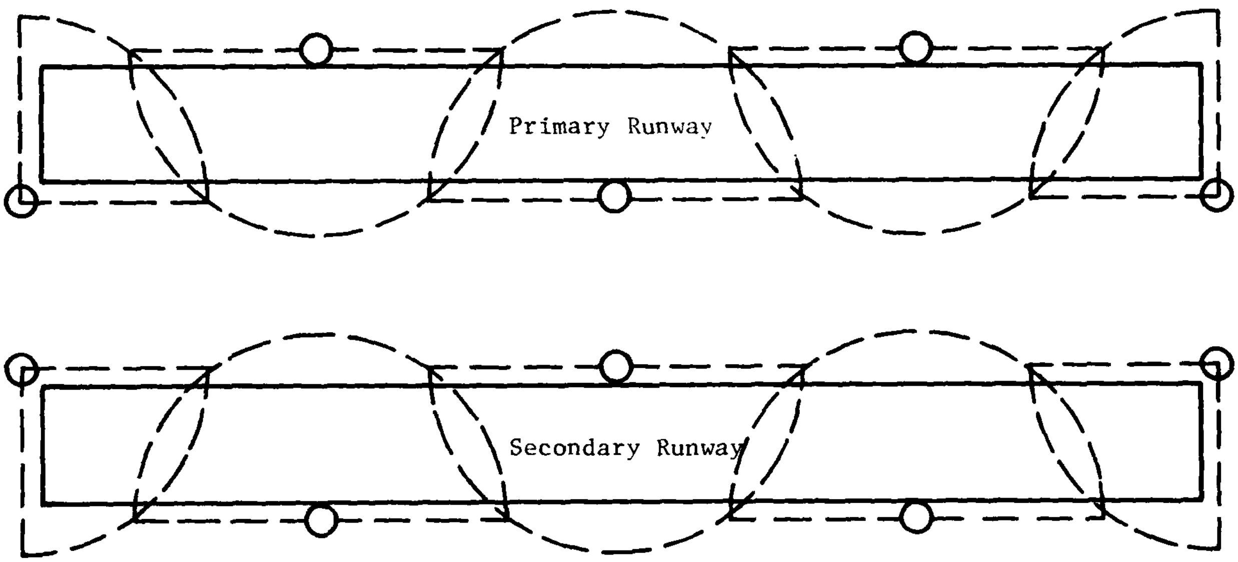
Overflight must be conducted in precise manner.

Scaling of crater size and pinpointing the exact location of the crater may be difficult unless special provision, such as a grid system, are added to the runway prior to the attack.

RUNWAY DAMAGE ASSESSMENT (RDA) PROCEDURE NO. 6	TELEVISION - HARD-MOUNTED AT SELECTED LOCATIONS

Procedure

1. Locate, design and install a television surveillance system which will allow complete coverage of both primary and secondary runways. Cameras must be placed to provide sufficient detail to allow remote determination of extent and types of damage. Data collection and analyses capability should be included.



2. System is operated during the following attack to provide visual and digital information for analysis and selection of emergency runway site.

Advantages

Provides data for runway location selection in minimum time.

System could also fulfill other functions such as security, repair supervision, operations evaluation, etc.

Disadvantages

Very expensive.

Camera locations susceptible to attack.

May require artificial lighting under some circumstances.

Scaling of crater size and pinpointing the exact location of the crater may be difficult unless special provision, such as a grid system, are added to the runway prior to the attack.

RUNWAY DAMAGE ASSESSMENT (RDA) PROCEDURE NO. 7	PHOTOGRAPHY - AERIAL PHOTOGRAPHY

Procedure

1. Helicopter equipped with equipment and crew to take aerial photographs of attack area.

2. Crew launched upon completion of attack - proceeds to conduct overflights of runway area, using accepted aerial photographic techniques to film damage. Proper procedure could result in stereoscopic quality pictures.

3. Film is returned to command post for processing and evaluation.

4. Data is analyzed and emergency runway location selected. Helicopter launched to place centerline and boundary markers.

Advantages

Provides accurate data.

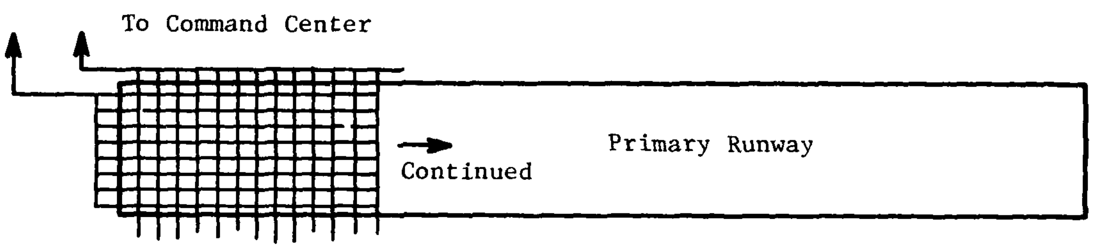
Disadvantages

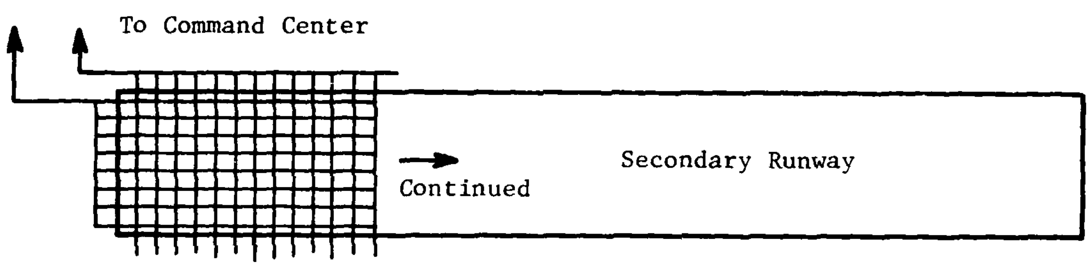
Very slow - processing alone requires approximately two hours.

RUNWAY DAMAGE ASSESSMENT (RDA) PROCEDURE NO. 8	ELECTRONIC - PREINSTALLED GRID SYSTEM

Procedure

1. An electronic sensing grid system would be designed and installed in each runway. This system would consist of conductive or resistive elements permanently installed in the concrete or subsurface of the runways and connected to appropriate display circuitry to allow command personnel to determine areas of damage during and after attack.





Advantages

Provides rapid data on damaged areas.

Minimal risk to personnel.

Disadvantages

Expensive - requires both development of system and installation of grid in existing runways.

Provides no information on presence of mined areas.

Provides little information of extent of damage other than size and location of craters.

RUNWAY DAMAGE ASSESSMENT (RDA) PROCEDURE NO. 9	ELECTRONIC - DIRECT CODED COMPUTER SYSTEM WITH INPUT FROM HELICOPTER BASED OBSERVER

Procedure

1. Computer system developed which would receive data from remote terminal (helicopter), evaluate data, and provide display and information upon which to base selection of emergency runway.

2. Following attack, helicopter would perform overflight of runway area. Observer would provide direct data input to system on locations and extent of runway damage, mined areas, and other pertinent information.

3. Based upon data received, computer would provide information and displays.

Advantages

Provides information to command center for evaluation and selection of emergency runway.

Provides rapid accurate data.

Disadvantages

Requires highly trained observer capable of providing fast, accurate direct data input.

RUNWAY DAMAGE ASSESSMENT (RDA) PROCEDURE NO. 10	TELEVISION - REMOTE PILOTED VEHICLE BASED

Procedure

1. Television equipped Remote Piloted Vehicle (RPV) launched before or during attack.

2. RPV flys predetermined course and speed over runway area. Video data is transmitted to command post. Location beacons (visual, electronic, or other type) at selected points will provide data for orientation of data.

3. Incoming video data displayed on monitor and also subjected to computer analysis and display on appropriate plotting board.

4. Command personnel evaluate information and select emergency runway - selection could be computer assisted.

5. Emergency runway coordinates provided to RPV operator - RPV equipped with markers could be used, or a helicopter could be launched for marking purposes.

   Note: This concept is similar to RDA Procedure No. 5., except for television platform.

Advantages

Fast $\leq$ 30 minutes for complete survey and marking.

Provides extensive, accurate data.

Allows command group selection of emergency runway location.

Allows all weather operation, with appropriate lenses and lighting.

Minimizes exposure of personnel to danger during and immediately following attack.

Back-up vehicles can be easily provided.

Frees helicopters and other personnel vehicles for other services.

Disadvantages

Expensive - requires development of RPV - television system, computer system.

Requires highly trained RPV operator.

RUNWAY DAMAGE ASSESSMENT (RDA) PROCEDURE NO. 11	TELEVISION - BALLOON BASES

Procedure

Function and operation of this concept is identical with RDA Procedure No. 10, except for television delivery system.

One or more balloons, equipped with television cameras and transmitters, would be permanently stored in hardened sites between primary and secondary runways. Upon ALL CLEAR, balloons would be launched, allowing television overview of entire runway area. Balloons would be tethered to allow viewing from preselected height.

Advantages

Fast $\leq$ 30 minutes for complete survey and marking.

Provides extensive, accurate data.

Allows command group selection of emergency runway location.

Allows limited adverse weather operation, with appropriate lenses and lighting.

Minimizes exposure of personnel to danger during and immediately following attack.

Back-up vehicles can be easily provided.

Frees helicopters and other personnel vehicles for other services.

Disadvantages

Expensive - requires development of remote controlled television data acquisition system and computer analysis interface.

Requires highly trained data analysis and computer operator.

High winds would limit usefulness of system.

RUNWAY DAMAGE ASSESSMENT (RDA) PROCEDURE NO. 12	RUNWAY GRID SYSTEM - ULTRAVIOLET MARKINGS (UV)

Procedure

This procedure could be used with the aid of a helicopter or be incorporated into any RDA procedure requiring overflight of runway area to determine damage, and would provide a means of accurately locating craters, delayed ordnance and mines.

All runway areas would be marked with an identifying grid system, using ultraviolet sensitive materials. This marking would not interfere with normal operations, but could be used to determine precise locations during RDA overflights with the use of appropriate ultraviolet viewing equipment.

Advantages

Provides an inexpensive means of marking runways which would not affect normal operations.

Disadvantages

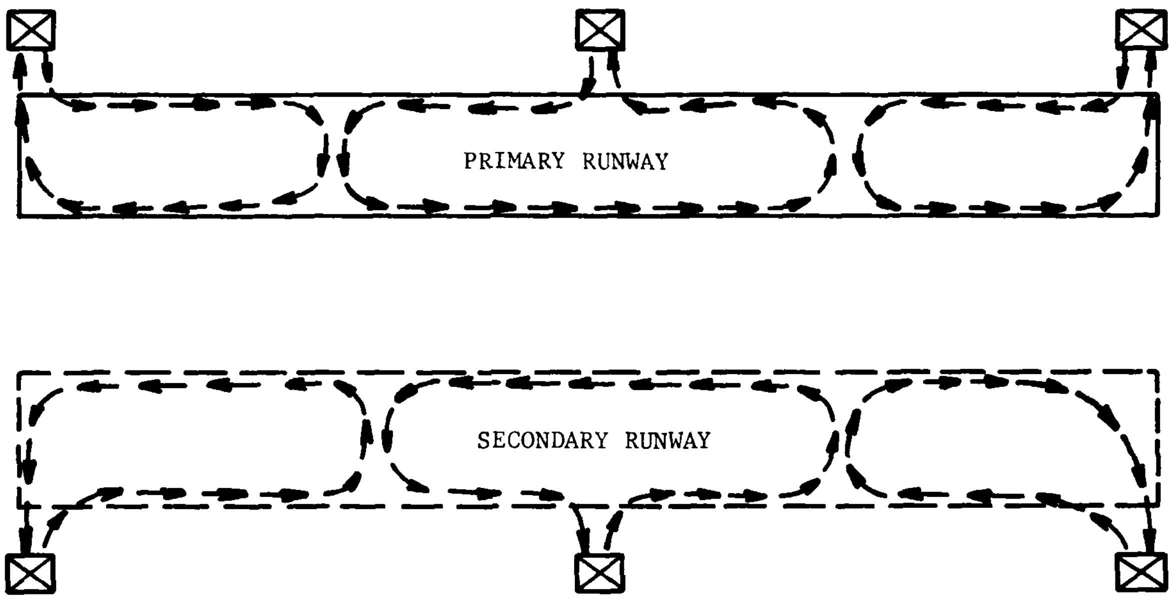
Requires ultraviolet viewing equipment.

May not be effective due to debris over much of airfield.

RUNWAY DAMAGE ASSESSMENT (RDA) PROCEDURE NO. 13	GROUND SURVEY - ARMORED VEHICLE WITH COMMUNICATION TO BASE COMMAND CENTER

Procedure

1. At time of alert, assemble armored vehicles and crews at selected hardened sites.



2. Upon ALL CLEAR survey crews leave shelters and conduct survey per diagram above. All data on location of damage, types of ordnance used, mined crews, EOD, etc., is radioed directly to command center where it is plotted and analyzed by command personnel. Each team to complete survey in approximately 10 minutes (average speed approximately 6 mph).

3. Command personnel evaluate data and select site of emergency runway. Radio coordinates of emergency runway centerline and boundaries to nearest survey crews.

4. Survey crews dispatch and mark emergency runway.

5. Mark taxiways and other accesses to emergency runway.

Advantages

Responsive - ≤ 30 minutes.

Uses available equipment.

Survey crew exposed to minimal risk and danger from mine and delayed bombs.

Survey crews need only minimal training.

Provides for command group decision on emergency runway location.

Disadvantages

Runway damage may preclude completion of survey by one or more teams.

Requires construction of hardened sites for crews.

Operations affected by weather, nighttime operations.

APPENDIX B

SOIL COMPACTION AND COMPACTORS

Compaction of soils is a complex process in which several soil properties as well as compactor characteristics interact. General rules have been developed through years of experience in construction and through a need recently to increase the subbase and base strength of runways to accommodate higher aircraft wheel loads. General guidelines are adequate when there is no need for an accurate prediction of the number of compactor coverages required to effect a given level of soil compaction.

As a part of this program, it was necessary that an estimate be made of the time required to compact soil to a certain strength. A review of the literature indicated that little recent work has been done on compaction and on the modeling of the compaction process. Freitag (Reference 1) conducted an analysis of the trafficability of vehicles over soft soils using similitude modeling to predict the complex vehicle-soil interaction. Although the soil compaction criteria are different from those of trafficability, similitude modeling could also be applied to compaction. Waterways Experiment Station (WES) has conducted many compaction tests with several soil and compactor types. Literature on some of these tests was obtained (References 2 through 10), and the raw data were used to structure a compaction model.

There are two generally accepted measures of compactive strength: the shear strength of the soil and its density. The shear strength is indicated by the California Bearing Ratio (CBR) which is determined by comparing the bearing value obtained from an arbitrary penetration-type shear test with a standard bearing value obtained from an arbitrary penetration-type shear test with a standard bearing value obtained on crushed rock. The compaction model, then, was structured to predict the CBR and the density of the soil after compaction. Table B-1 is a compilation of the compaction data used to generate the CBR models. The left-hand portion of the table indicates the WES report reference from which the data was extracted and the experimental data. The asterisk indicates that the tabular value given was assumed. In many instances there was insufficient information available in the reports to allow a value to be estimated. Those data points have not been included in the table.

The information on the right-hand portion of the table are the calculated values. It was assumed that the CBR model would be of the form:

$$\frac{CBR}{W/bR} = K \cdot W_F \cdot N_F \cdot U_F \cdot \omega_F \cdot h_F \cdot R_F \cdot \mu_F \qquad \text{(B-1)}$$

where

W = Compactor Weight, Lb

b = Width of Compactor Drum, Ft

R = Radius of Compactor Drum, Ft

CBR = California Bearing Ratio, %

TABLE B-1. CBR DATA

ID NO.	SOIL TYPE	REFERENCE	COMPACTOR TYPE	W LB	R FT	b FT	ρ_o LB/FT^3	h_o FT	PI	u_o %	N	U FPS	CBR %	W_F	N_F	U_F	h_F	R_F	P_F	Predicted $\frac{CBR}{W/br}$	Experimental $\frac{CBR}{W/br}$
1	Lean Clay	TH3-271-6	Sheepsfoot Roller	14,000	2.79	11.0	75	0.5	18	16.5	.33	4.4	10	.043	.778	1.374	.017	.816	.775	.025	.022
2										21.0	.33		1		.778				.269	.009	.002
3										18.5	.33		6		.778				.576	.019	.013
4										15.0	.67		18		.913				.888	.034	.039
5										17.0	.67		13		.913				.730	.028	.028
6										19.0	.67		6		.913				.519	.020	.013
7										14.0	1.33		25		1.066				.942	.042	.055
8										16.0	1.33		14		1.066				.817	.036	.031
9				14,000						18.0	1.33		5	.043	1.066				.631	.028	.011
10				28,000						16.0	.33		12	.025	.778				.817	.016	.013
11										18.0	.33		10		.778				.631	.012	.011
12										20.0	.33		7		.778				.398	.008	.008
13										15.0	.67		19		.913				.888	.020	.021
14										16.5	.67		17		.913				.775	.018	.019
15										19.0	.67		12		.913				.519	.012	.013
16										12.5	1.33		31		1.066				.991	.026	.034
17										14.8	1.33		25		1.066				.900	.024	.027
18				28,000						16.5	1.33		19	.025	1.066				.775	.021	.021
19				42,000						14.5	.33		21	.019	.778				.917	.013	.015
20										16.5	.33		16						.775	.011	.012
21										18.5	.33		11		.778				.576	.008	.008
22										14.0	.67		23		.913				.942	.016	.017
23										15.4	.67		20		.913				.861	.014	.015
24										18.0	.67		11		.913				.631	.010	.008
25										12.0	1.33		44		1.066				.998	.019	.032
26										13.5	1.33		37		1.066				.963	.019	.027
27	Lean Clay	TH3-271-6		42,000					18	16.0	1.33		20	.019	1.066				.817	.016	.015
28	Clayey Sand	TH3-271-1		14,000					2	12.7	.50		8	.021	.855				.986	.018	.017
29	Clayey Sand	TH3-271-1	Sheepsfoot Roller	25,200	2.79	11.0		0.5	2	12.4	.50	4.4	9	.014	.855	1.374	.017	.816	.992	.011	.011
30			Tractor	34,500	4.75	3.67				13.5	3.00		6	.007	1.282	1.533	.005	1.039	.963	.004	.003
31			Tandem Roller	80,000	4.95	4.0				12.2	8.00		8	.004	1.600	1.207	.004	1.032	.995	.002	.001
32			Tandem Roller	160,000	4.95	4.0				12.2	8.00		6	.002	1.600	1.207	.004	1.032	.995	.001	.001
33	Clayey Sand	TH3-271-1	Tandem Roller	160,000	4.95	4.0	75	0.5	2	12.2	16.00	4.4	8	.002	1.871	1.207	.004	1.032	.995	.004	.001

TABLE B-1. CBR DATA (CONTINUED)

ID NO.	SOIL TYPE	REFERENCE	COMPACTOR TYPE	W LB	R FT	b FT	ρ_o LB/FT^3	h_o FT	PI	ν_o %	N	U FPS	CBR %	W_F	N_F	U_F	h_F	R_F	P_F	Predicted $\frac{CBR}{W/br}$	Experimental $\frac{CBR}{W/br}$
34	Lean Clay	TH-3-271-7	Rubber Tire Roller	63,500	1.75	8.0	75	0.5	15	19.5	4	4.4	9	.007	1.368	.974	.009	.798	.495	.0020	.0020
35		TH-3-271-7		63,500					15	19.2	8		9	.007	1.600				.495	.0025	.0020
36		TH-3-271-7		100,000					15	17.5	4		10	.005	1.368				.682	.0021	.0014
37		TH-3-271-7							15	17.0	8		14		1.600				.730	.0023	.0020
38		TH-3-271-8							17	12.0	8		22						.998	.0039	.0031
39									17	12.3	8		21						.994	.0039	.0029
40									17	15.2	8		25						.875	.0034	.0035
41									17	20.3	8		4		1.600				.360	.0013	.0006
42								0.5	15	14.7	16		28	.005	1.871		.009		.906	.0039	.0039
43								0.1	17	10.5	8		16	.009	1.600		.003		.991	.0022	.0022
44										12.7			16						.986	.0021	.0022
45										17.5			14						.682	.0015	.0020
46										20.0			4						.398	.0009	.0006
47										11.0			10						.998	.0022	.0014
48										13.5			16						.963	.0021	.0022
49								1.0		18.6			7	.009					.565	.0012	.0010
50								2.0		11.1			23	.015					.998	.0036	.0032
51										14.1			20						.937	.0034	.0028
52										15.7			17						.840	.0031	.0024
53										20.3			3						.360	.0013	.0004
54										11.3			9						1.000	.0037	.0013
55										16.5			11						.775	.0028	.0015
56				100,000				2.0		20.8	8		3	.015			.003		.295	.0011	.0004
57				125,000				0.5		12.0	8		30	.004			.009		.998	.0033	.0034
58								0.5		14.0			32				.009		.942	.0031	.0036
59								0.5		17.0			12				.009		.730	.0024	.0013
60								0.5		19.5			5	.004			.009		.459	.0015	.0006
61								1.0		11.9			21	.007			.003		.998	.0018	.0023
62										14.8			18						.900	.0017	.0020
63										16.5			15						.775	.0014	.0017
64										19.6			5			.974			.447	.0008	.0006
65										12.4			26						.992	.0018	.0029
66										16.4			16						.784	.0014	.0018
67	Lean Clay	TH-3-271-8	Rubber Tire Roller	125,000	1.75	8.0	75	1.0	17	17.9	8	4.4	7	.007	1.600		.003	.798	.641	.0012	.0008

TABLE B-1. CBR DATA (CONTINUED)

ID NO.	SOIL TYPE	REFERENCE	COMPACTOR TYPE	W LB	R FT	b FT	ρ_o LB/FT^3	h_o FT	PI	ν_o %	N	U FPS	CBR %	W_F	N_F	U_F	h_F	R_F	P_F	Predicted CBR W/br	Experimental CBR W/br
68	Lean Clay	TH-3-271-8	Rubber Tire Roller	125,000	1.75	8.0	75	1.0	17	19.3	8	4.4	8	.007	1.600	.974	.003	.798	.483	.0009	.0009
69								2.0	17	15.2	8	4.4	20	.013	1.600	.974	.003		.875	.0027	.0022
70										16.4			23						.784	.0024	.0026
71										18.5			17						.576	.0018	.0019
72										10.1			28						.982	.0030	.0031
73										14.2			24						.933	.0029	.0027
74										16.1			14						.809	.0025	.0016
75	Lean Clay	TH-3-271-8		125,000	1.75	8.0	75	2.0	17	18.9	8	4.4	11	.013	1.600	.974	.003		.531	.0016	.0012
76																					
77																					
78	Crushed	TH-3-271-9		100,000	1.75	8.0		.33	0	0.9	8	4.4	34	.002	1.600		.078		.368	.003	.005
79	Limestone 1-1/2"									1.9			52						.714	.006	.007
80	Maximum									3.6			45						.998	.008	.006
81										4.0			56						.994	.008	.008
82										4.8	8		45		1.600				.905	.008	.006
83										0.6	32		37		2.188				.249	.003	.005
84										1.8			61						.684	.008	.008
85										2.4			96						.844	.010	.013
86										3.1			78						.963	.011	.011
87	1-1/2" Max.									3.6	32		69		2.188				.998	.012	.010
88	3/4" Max.									0.4	8		16		1.600				.167	.001	.002
89										1.9			30						.714	.006	.004
90										3.3			20						.982	.008	.003
91										3.5			30						.994	.008	.004
92										3.9			31		1.600				.998	.008	.004
93										0.3	32		24		2.188				.125	.001	.003
94										1.6			32						.621	.007	.004
95										2.3			67						.821	.010	.009
96	3/4" Max.			100,000	1.74	8.0				2.6	32		60	.002	2.188	.974	.078		.886	.010	.008
97	1-1/2" Max.			120,000	1.54	7.0				1.3	8		40	.001	1.600	1.215	.078		.518	.004	.003
98										3.2	8		54						.973	.007	[illegible]
99	Crushed Limestone									3.9	8		58						.998	.008	[illegible]
100	1-1/2" Max.	TH-3-271-9	Rubber Tire Roller	120,000	1.54	7.0	75	.33	0	5.8	8	4.4	10	.001	1.600	1.215	.078	.798	.653	.005	.009

TABLE B-1. CBR DATA (CONCLUDED)

ID NO.	SOIL TYPE	REFERENCE	COMPACTOR TYPE	W LB	R FT	b FT	ρ_o LB/FT^3	h_o FT	PI	ν_o %	N	U FPS	CBR %	W_F	N_F	U_F	h_F	R_F	P_F	Predicted $\frac{CBR}{W/br}$	Experimental $\frac{CBR}{W/br}$
101	Crushed Limestone 1-1/2" Max.	TH-3-271-9	Rubber Tire Roller	120,000	1.54	7.0	75	.33	0	1.4	16	4.4	52	.001	1.871	1.215	.078	.799	.553	.005	.005
102										2.3	16		65		1.871				.821	.007	.006
103										2.6	16		66		1.871				.886	.009	.006
104										4.9	16		7		1.871				.886	.008	.001
105										1.7	32		60		2.188				.653	.007	.005
106										3.8	32		86		2.188				.999	.010	.008
107										4.3	32		59		2.188				.973	.010	.005
108	1-1/2" Max.									5.1	32		5		2.188				.844	.009	.000
109	3/4" Max.									1.3	8		40		1.600				.518	.004	.003
110										2.8	8		46		1.600				.922	.007	.004
111										4.7	8		16		1.600				.922	.007	.001
112										6.6	8		13		1.600				.368	.003	.001
113										1.2	16		47		1.871				.482	.004	.004
114										2.7	16		49		1.871				.965	.008	.004
115										4.6	16		35		1.871				.937	.008	.003
116										7.0	16		9		1.871				.208	.002	.001
117										1.2	32		49		2.188				.482	.005	.004
118	3/4" Max.									1.8	32		63		2.188				.684	.007	.006
119	Crushed Limestone									3.5	32		59		2.188				.994	.010	.005
120		TH-3-271-9	Rubber Tire Roller	120,000	1.54	7.0	75	.33	0	6.1	32	4.4	9	.001	2.188	1.215	.078	.799	.553	.006	.001

K = Constant

W_F = Weight Factor

N_F = Coverage Factor

U_F = Speed Factor

ω_F = Frequency Factor

One is used depending on the type of compactor.

h_F = Lift Factor

R_F = Bearing Factor

μ_F = Moisture Factor

The problem was to establish a relationship which will consider each of the factors. This was accomplished by postulating a grouping of parameters which were likely to characterize each factor, postulating a relationship for each factor, and testing this relationship against the data available. It became evident that a relationship for a particular factor could be estimated, but this relationship was generally soil and/or compactor peculiar to some extent. The accuracy with which the CBR relation was modeled is shown by the extreme right-hand columns of Table B-1, which compare predicted to experimental values of CBR/W/bR. As the models were developed, it became evident that, if complete experimental data exists, the CBR could be modeled very accurately for a given set of experiments. This accuracy fell off, however, across a series of experiments reported in different documents. Part of this loss of accuracy is due to the error in measurement, and part is due to the inherent inaccuracy of the model in its current state of development. The ability to fine tune the model, however, was useful in the characterization of the lift factor, which would otherwise have presented a strong source of inaccuracy.

Figure B-1 shows the correlation of predicted to experimental data for the compaction of clayey sand using sheepsfoot, tractor, or rubber-tired rollers. For perfect prediction, the points should fall on the line exactly. For these conditions, then, the CBR model is of the form:

$$\frac{CBR}{W/bR} = 51.4128 \left[\left(\frac{\rho_o h_o}{W/bR} \right)^{(.0037\ PI) + .11} \right]^{.831} [N]^{.226} \left[\frac{U^2}{Rg} \right]^{.207} \left(\frac{R}{h_o} \right)^{-2.365} \left[\frac{R}{b} \right]^{.185} [\mathrm{Sin}(7.828\mu_o)] \qquad \text{(B-2)}$$

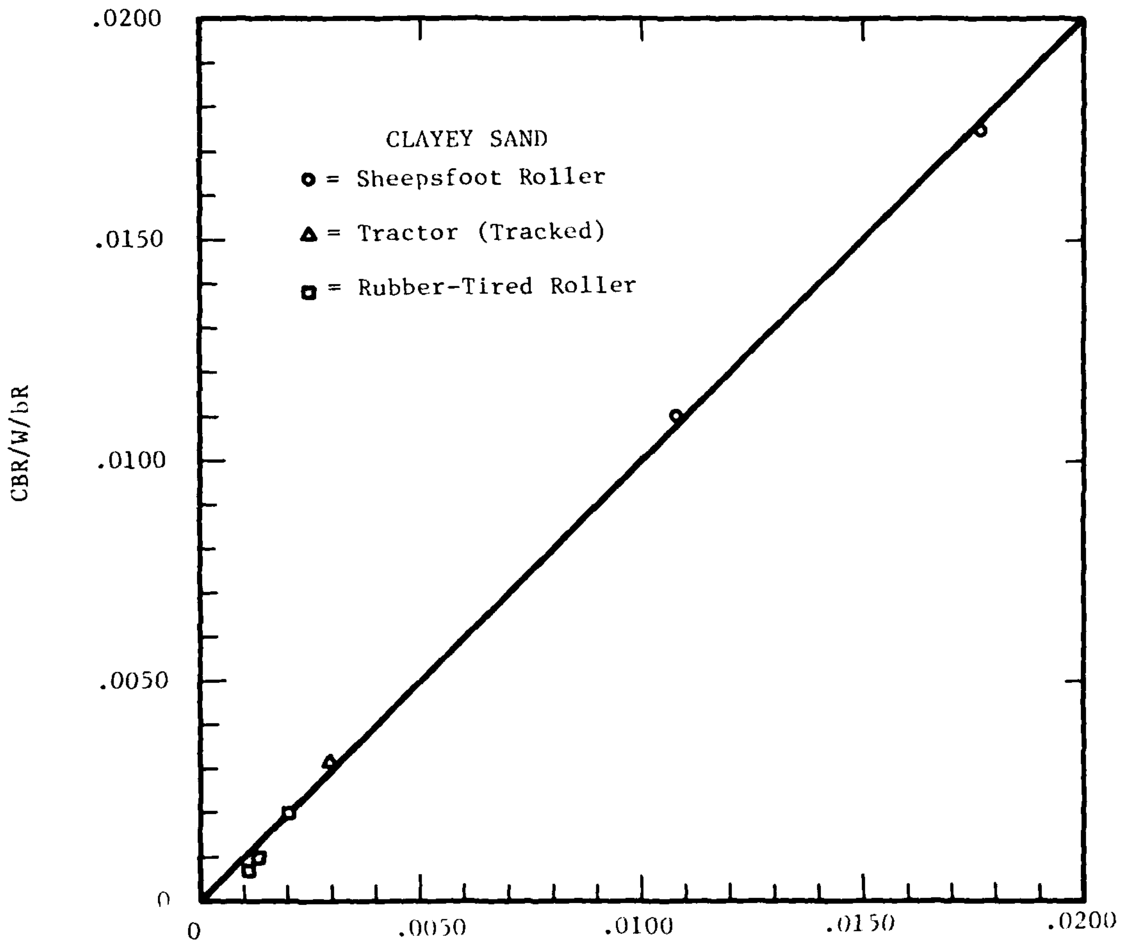
where ρ_o = Initial Density of Soil, Lb/Ft^3

h_o = Initial Lift Height, Ft

PI = Plasticity Index of Soil

N = Number of Coverages

U = Vehicle Speed, Ft/Sec



$$51.4128\left[\left(\frac{\rho_o h_o}{W/bR}\right)(.0037PI + .11)\right]^{.831}[N]^{.226}\left[\frac{U^2}{Rg}\right]^{-.207}\left[\frac{R}{h_o}\right]^{-2.365}\left[\frac{R}{b}\right]^{.185}\{\mathrm{Sin}(7.828\mu_o)\}$$

Figure B-1. Compaction Versus Compactor Characteristics

g = Gravitational Constant, Ft/Sec^2

μ_o = Moisture of Soil, Percent of Dry Weight

Figure B-2 shows the same relation for the impact compactor for lean clay. The CBR prediction takes the form:

$$\frac{CBR}{W/bR} = 51.4128 \left[\left(\frac{\rho_o h_o}{W/bR}\right)(.0037\ PI + .11)\right]^{.831} [N]^{.228} \left[\frac{\omega U}{g}\right]^{-.410} \left[\frac{R}{h_o}\right]^{-2.365} \left[\frac{R}{b}\right]^{.1485} [\mathrm{Sin}(7.828\mu_o)] \qquad \text{(B-3)}$$

where ω = Vibrational Frequency, Radians/Second.

An examination of Figure B-2 shows a point in which the predicted value does not compare favorably with the experimental value. This particular data point represents a relatively high lift which, in turn, relates to a different $\left(\frac{R}{h_o}\right)$ term than that given in Equations (B-1) and (B-2). It is clear, however, that Equations (B-1) and (B-2) are similar except for the terms relating to the vibrational factor, $\left(\frac{\omega U}{g}\right)$, and the bearing factor.

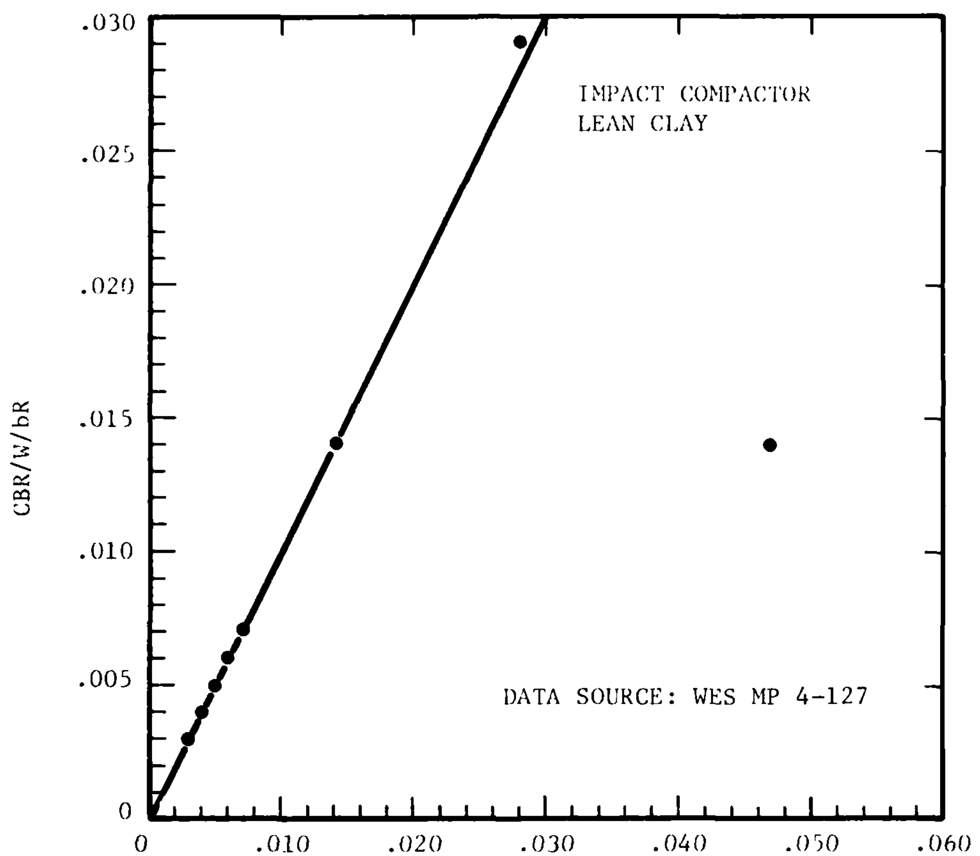
As other soils and other compactors were modeled, it became clear that the lift factor was not a simple relationship. The lift factor was, therefore, modeled as the dependent variable for a series of data points over a range of $\frac{h_o}{R}$. The result was the relationship shown in Figure B-3. It must be cautioned that the relationship shown is commensurate with the current state of the compaction model. Clearly, more analysis is required before the relationship can be verified. However, the data points shown cover a wide range of cohesive soils and compactor types. If the relationship is even approximately accurate, it could explain some of the scatter in the experimental data. It would be expected that lift heights from 10 to 40 percent of the drum radius would have to be recorded accurately to preclude the inducement of inaccuracies of data trends. Unfortunately, much of the experimental data is in this region.

Figure B-4 illustrates the prediction of compaction capability in lean clay and clayey sand for the sheepsfoot roller, the tandem roller, and the tractor. In general, the prediction is not too bad considering the state of the model. The prediction is of the form:

$$\frac{CBR}{W/bR} = 51.4128 \left[\left(\frac{\rho_o h_o}{W/bR}\right)(.0067\ PI + .00596)\right]^{.750} [N]^{.226} \left[\frac{U^2}{Rg}\right]^{-.207} [h_F] \frac{R}{b}^{.1485} [\mathrm{Sin}(7.828\mu_o)] \qquad \text{(B-4)}$$

where h_F = Lift Factor (see Figure B-3).

Equation (B-3) bears a family resemblance to Equation (B-1). The weight factor relation has been modified to allow a more general application of the relation, and the lift factor has been listed as a particular factor which is determined from Figure B-3.



$$51.4128\left[\left(\frac{\rho_o h_o}{W/bR}\right)(.0037\ PI + .11)\right]^{.831}\left[\frac{R}{b}\right]^{.1485}[\mathrm{Sin}\ 7.828\mu_o][N]^{.226}\left[\frac{\omega U}{g}\right]^{-.410}\left[\frac{R}{h_o}\right]^{-2.365}$$

Figure B-2. Compaction Versus Compactor Characteristics

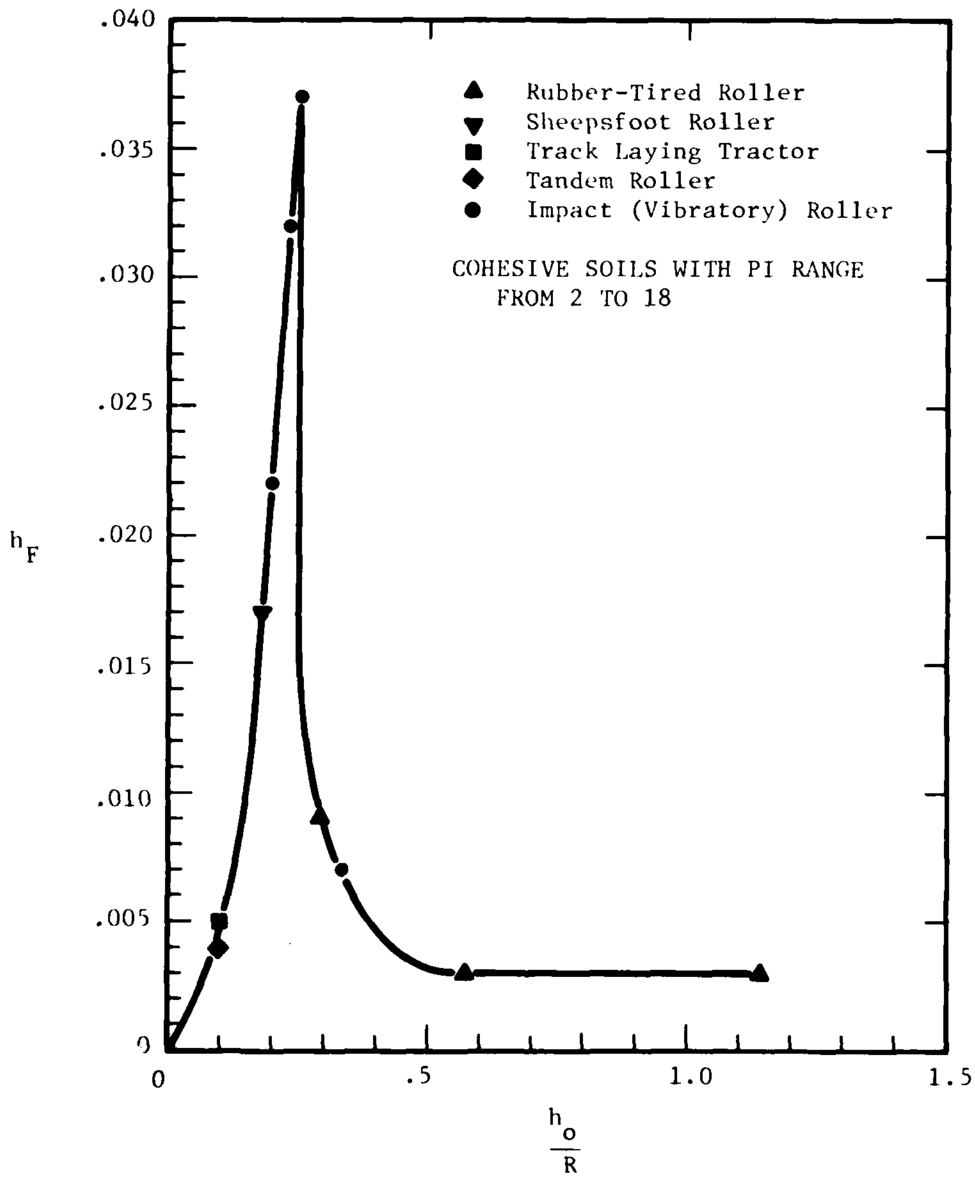
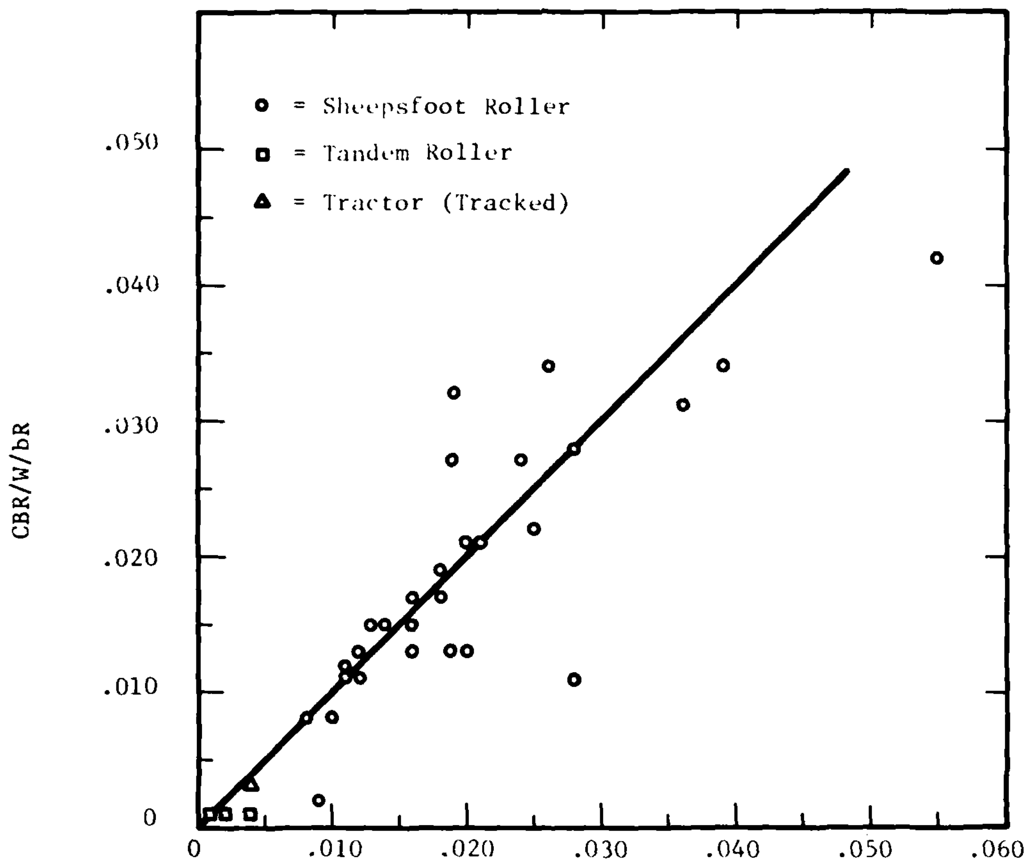


Figure B-3. Lift Factor (h_F) Versus Lift Height to Compactor Drum (Or Wheel) Radius $\left(\frac{h_o}{R}\right)$



$$51.4128\left[\left(\frac{\rho_o h_o}{W/bR}\right)(.0067PI + .00596)\right]^{.750}[N]^{.226}\left[\frac{U^2}{Rg}\right]^{-.207}[h_F]\left(\frac{R}{b}\right)^{.1458}[\mathrm{Sin}(7.828\mu_o)]$$

Figure B-4. Compaction Versus Compactor Characteristics

Figure B-5 shows the correlation between predicted and experimental data for lean clay and the rubber-tired roller. Note the scale shift between Figure B-3 and Figure B-4. The scale for the rubber-tired roller is magnified by an order of magnitude over that for the other rollers. The distribution of the data indicates that the trend is correct, but the equation should be adjusted somewhat to provide a better prediction.

Figure B-6 shows the correlation for crushed limestone. There is considerably more scatter to the correlation primarily because there is considerably more scatter in the experimental data. The trend could be adjusted to achieve a somewhat better fit; however, it is probable that the CBR test begins to lose its value for a material such as crushed limestone. The equation is of the form:

$$\frac{CBR}{W/bR} = 51.4128 \left[\left(\frac{\rho_o h_o}{W/Br}\right) (.0067\ PI + .00596\right]^{.750} [N]^{.226} \left[\frac{U^2}{Rg}\right]^{-.207} (.078)\left[\frac{R}{b}\right]^{.1485} [\mathrm{Sin}(24.0\mu_o)] \qquad \text{(B-5)}$$

Equation (B-5) is similar to Equation (B-4) except h_F is replaced by a constant and the moisture factor has been modified.

There exists considerable additional data which has not been included in the model. Additional reports have been received since the models were initiated. In general, however, it can be concluded that if the experiments are reported accurately enough to allow a duplication of the experiment, the CBR relation can be modeled.

As with the CBR model, the density model has been formulated as a group of dimensionless factors of the form:

$$\frac{Pi}{W/bh_oR} = K \cdot W_F \cdot N_F \cdot \omega_F \cdot U_F \cdot h_F \cdot R_F \cdot \mu_F \qquad \text{(B-6)}$$

Equation (B-6) is similar to Equation (B-1) except Pi = Soil density (dry) after compaction, Lb/Ft^3.

In general, the density model is more soil and compactor peculiar than is the CBR model. This indicates that the model needs additional refinement before a general compaction model can be presented. The predictability of the density model, however, appears to be somewhat better than that of the CBR model for some soil types.

Table B-2 presents the π terms of the model for each soil type investigated. In addition, compactor peculiar terms are indicated. The parameters are those given in the last progress report. From this table it is evident that:

- The weight factor is influential only for the lean clay. The basic term of the weight factor is also evident in the moisture factor, which is the primary influence in the

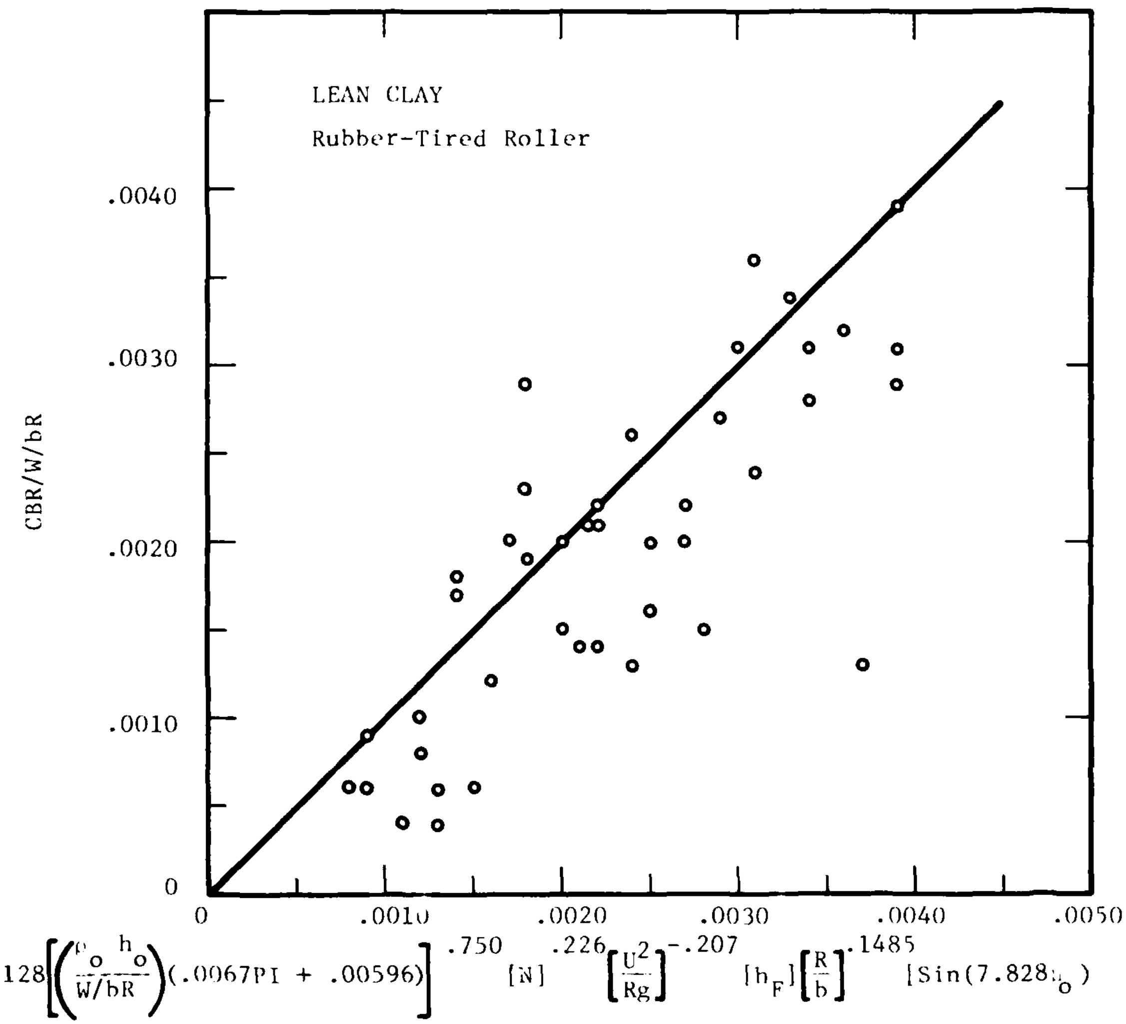
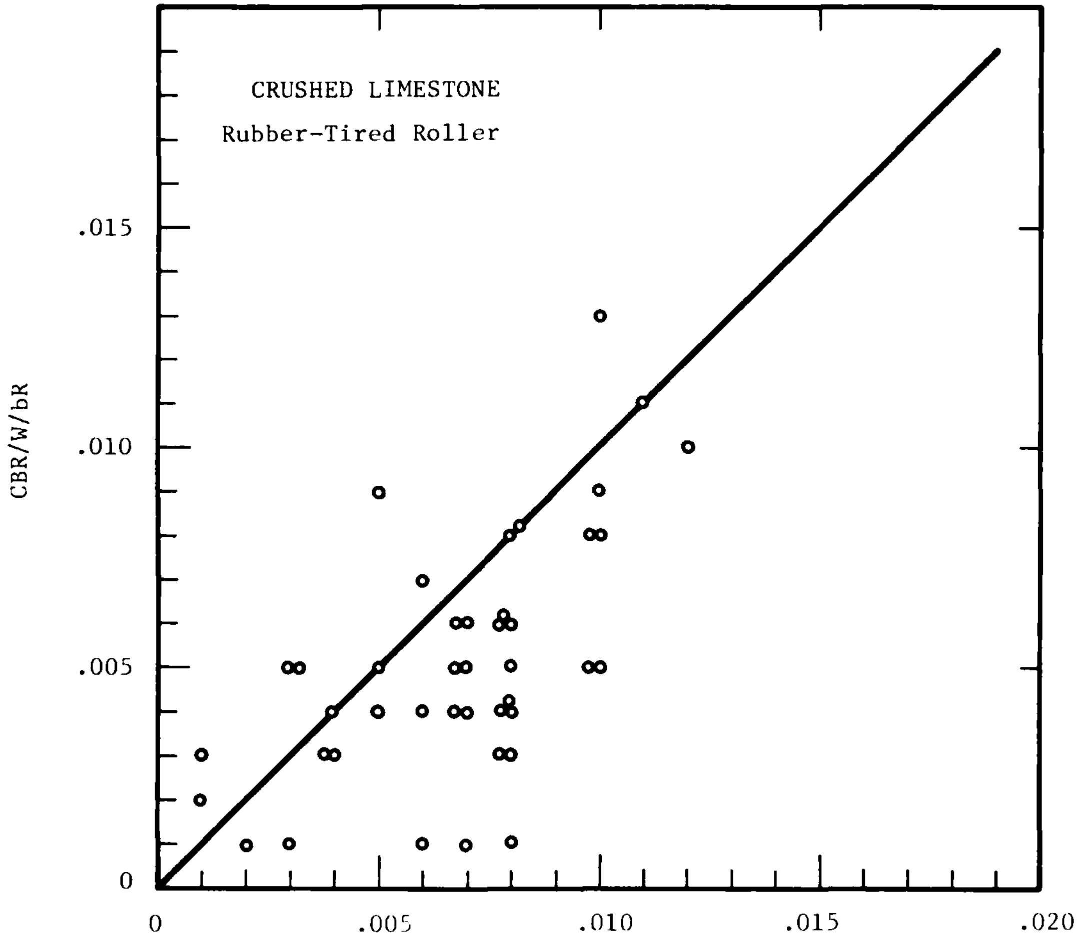


Figure B-5. Compaction Versus Compactor Characteristics



$$51.4128\left[\left(\frac{\rho_o h_o}{W/bR}\right)(.0067PI + .00596)\right]^{.750} [N]^{.226}\left[\frac{U^2}{Rg}\right]^{-.207} (.078)\left[\frac{R}{b}\right]^{.1485} [\mathrm{Sin}(24.0\mu_o)]$$

Figure B-6. Compaction Versus Compactor Characteristics

TABLE B-2. DENSITY MODEL π TERMS

SOIL TYPE	CONSTANT K	WEIGHT FACTOR W_F	COVERAGE FACTOR N_F	FREQUENCY FACTOR ω_F	SPEED FACTOR U_F	LIFT FACTOR h_F	BEARING FACTOR R_F	MOISTURE FACTOR μ_F	COMPACTOR TYPE
Lean Clay	0.456	$\frac{\rho_o}{W/bh_oR}(PI + .1)^{.05}$	$N^{.11}$	$\left(\frac{\omega U}{g}\right)^{-.005}$	$\left(\frac{U^2}{Rg}\right)^{-.075}$	$\left(\frac{h_o}{R}\right)^{-.047}$	$\left(\frac{R}{b}\right)^{-.057}$	$\frac{\rho_o}{W/bh_oR} + \left(\frac{\rho_o}{W/bh_oR}\right)^{.803} \text{Sin } 4.74\mu_o$	Vibratory
		$\frac{\rho_o}{W/bh_oR}(PI + .1)^{.10}$	$N^{.08}$						Rubber-Tired
			$N^{.04}$						Sheepsfoot
Clayey Sand	0.725	1.0	$N^{.005}$	NO DATA	1.0			$\frac{\rho_o}{W/bh_oR}(1 + \text{Sin } 4.74\mu_o)$	All
Sand	0.612		$N^{.112}$	1.0	$\left(\frac{U^2}{Rg}\right)^{.087}$			$\frac{\rho_o}{W/bh_oR}(1 + \text{Sin } 3.83\mu_o)$	
Crushed Limestone	0.914		$N^{.018}$		$\left(\frac{U^2}{Rg}\right)^{-.008}$			$\frac{\rho_o}{W/bh_oR} + \left(\frac{\rho_o}{W/bh_oR}\right)^{3} (\text{Sin } 15.0\mu_o)$	

relationship. The weight factor, then, reflects the cohesiveness of the soil (PI) which tends to disappear with clayey sand, sand, and limestone.

- The coverage factor varies according to soil and compactor type. For clayey sand the coverage factor effect is very small; however, the sample size for this particular soil type was also small.

- The vibrational frequency did not show a strong influence in the data available. Indeed, except for lean clay, the frequency effect is negligible -- over the frequency range investigated (44 to 377 rad/sec). It should be noted that the vibratory is added to the static weight of the compactor to estimate the weight of compaction.

- The speed factor shows a small influence. An inspection of the basic data indicates that all of the compaction tests were conducted at the same speed. This factor, then, could not be adequately defined, and the speed effect is primarily a compactor radius (R) effect.

- Unlike the lift factor effect for CBR, the lift factor for density is relatively constant. There was a very slight soil/compactor influence; however, it was small enough to be ignored.

- The bearing factor effect is relatively small and the exponent is negative (the exponent is positive for the CBR).

- The moisture factor effect is the primary influence in the density model. This is primarily due to the influence of the initial density factor (Po/W/BhoR). Although it is somewhat dangerous to draw conclusions based on limited data, the trend of the exponent of the second term is an increasing function with increased soil grain size. The coefficient in front of the moisture (μ_o) depends on the critical moisture of the soil relative to the density-moisture relation. The density critical moisture appears to differ from the CBR critical moisture.

The data base for the density model as well as the π terms are given in Table B-3. The two right-hand columns compare the predicted density factor to the experimental density factor. In general, the agreement is good, although there are some test sequences for which the agreement could be better. It should be noted that some data had to be assumed so that the analysis could be conducted. Within a given set of experiments, the exact value of the assumed parameters can be compensated for by the constant (K); however, when data is analyzed across a group of seemingly similar experiments, a bias is experienced if that assumed value did indeed vary from group to group.

The error for each experimental and predicted density factor was calculated using the experimental value as the correct value. The average error of the density model for each soil type and compactor type is given in Table B-4. From this table it is seen that the model predicts the compacted density with a reasonable degree of accuracy. Indeed, if a closely

TABLE B-3. DENSITY DATA

*Assumed

SOIL TYPE	REFERENCE	COMPACTOR TYPE	ω	W LB	R FT	b FT	ρ_o LB/FT^3	h_o FT	PI	μ_o %	N	U FPS	ρ LB/FT^3	K	ω_F	W_F	N_F	U_F	h_F	R_F	μ_F	PREDICTED $\frac{\rho}{W/bh_oR}$	EXPERIMENTAL $\frac{\mu}{W/bh_oR}$
Lean Clay	TM3-271	Sheepsfoot Roller	0	28,000	2.79	11.0	75*	0.5	18	18.0	.33	4.4	106.0	.456	1.0	.97	.957	1.122	1.084	1.081	.1006	.0560	.0561
										20.0	.33		105.0				.957				.1006	.0560	.0575
										15.0	.67		106.0				.984				.0976	.0559	.0581
										16.5			107.2								.0995	.0569	.0587
										19.0	.67		105.9				.984				.1008	.0577	.0580
										12.5	1.33		106.0				1.011				.0924	.0543	.0581
										14.8			110.0								.0973	.0572	.0603
										16.5			108.6								.0995	.0585	.0595
										12.2			104.2								.0916	.0539	.0571
										11.9			103.9								.0908	.0534	.0569
										11.9			107.5								.0908	.0534	.0589
										18.1			106.3								.1006	.0592	.0582
										18.0			107.2								.1006	.0592	.0587
										18.1			107.2								.1006	.0592	.0587
										20.4			104.2								.1004	.0590	.0579
										20.0			108.7								.1006	.0592	.0596
				28,000						20.1	1.33		106.8			.97	1.011				.1005	.0591	.0585
				42,000						9.6	.33		101.2			.93	.957				.0572	.0305	.0370
										10.2			103.3								.0586	.0313	.0377
										10.2			103.1								.0586	.0313	.0377
										17.6			106.5								.0689	.0368	.0389
										16.4			106.2								.0682	.0364	.0388
										17.4			102.6								.0688	.0367	.0375
										20.2			108.6								.0689	.0368	.0397
										20.5			106.6								.0688	.0367	.0389
										19.4			108.3								.0691	.0369	.0396
										14.5			106.0								.0663	.0354	.0387
										16.5			107.2								.0683	.0364	.0392
										18.5	.33		106.0				.957				.0691	.0369	.0387
										14.0	.67		106.9				.984				.0656	.0360	.0390
										15.4			109.0								.0673	.0369	.0398
										18.0	.67		107.0				.984				.0690	.0379	.0391
										12.0	1.33		109.5				1.011				.0624	.0352	.0400
										13.5			112.5								.0649	.0366	.0411
										16.0			111.2								.0679	.0383	.0406
										11.4			112.5								.0612	.0345	.0411
				42,000						11.2	1.33		110.1			.93	1.011				.0608	.0343	.0402
				14,000						12.3	.33		103.5			1.04	.957				.1759	.1050	.1134
										12.7			105.4								.1777	.1061	.1155
										12.3			103.9								.1759	.1050	.1139
										21.0			103.4								.1908	.1139	.1135
										20.9			103.6								.1909	.1139	.1135
										20.7			105.2								.1912	.1141	.1153
										21.3			103.8								.1903	.1136	.1138
										16.5			104.0								.1900	.1134	.1140
										18.5	.33		105.2								.1922	.1147	.1153
										15.0	.67		105.9				.984				.1864	.1144	.1161
										17.0			106.5								.1908	.1171	.1167
										19.0	.67		106.0				.984				.1923	.1180	.1162
										11.2	1.33		103.2				1.011				1702	.1073	.1131
										12.7			108.9								.1778	.1121	.1194
										10.6			102.5								.1669	.1052	.1123
Lean Clay	TM3-271	Sheepsfoot Roller	0	14,000	2.79	11.0	75*	0.5	18	11.6	1.33	4.4	[illegible]	.456	1.0	1.04	1.011	1.122	1.084	1.081	.1724	.1087	.1124

TABLE B-3. DENSITY DATA (CONTINUED)

*Assumed

SOIL TYPE	REFERENCE	COMPACTOR TYPE	ω	W LB	R FT	b FT	γ_o LB/FT^3	h_o FT	PI	ω_o %	N	V PPS	γ LB/FT^3	K	[illegible]$_F$	W_F	N_F	U_F	h_F	R_F	μ_F	PREDICTED $\frac{\rho}{W/bh_oR}$	EXPERIMENTAL $\frac{\rho}{W/bh_oR}$
Lean Clay	TM3-271	Sheepsfoot Roller	0	14,000	2.79	11.0	75*	0.5	[illegible]	[illegible]	1.33	4.4	106.4	.456	1.0	1.04	1.011	1.122	1.084	1.081	.1786	[illegible]	.1166
										12.7			[illegible]								.1778	.1121	.1161
										16.5			[illegible]								.1900	.1138	.1127
										17.0			104.4								.1903	.1203	.1144
										16.1			106.9								.1892	.1193	.1172
										21.7			98.7								.1896	.1196	.1082
										21.5			102.7								.1899	.1197	.1126
										21.2			100.2								.1905	.1201	.1198
										14.0			106.6								.1831	.1155	.1168
										16.0			108.2								.1890	.1192	.1186
				14,000						18.0	1.33		107.2			1.04	1.011				.1919	.1210	.1175
				28,000						11.3	.33		91.5			.97	.957				.0891	.0496	.0501
										11.5			104.3								.0897	.0499	.0572
										11.3			100.3								.0891	.0496	.0550
										17.1			104.0								.1001	.0557	.0570
										17.8			105.0								.1005	.0559	.0575
										18.4			103.4								.1007	.0561	.0567
										19.3			106.9								.1008	.0561	.0586
										19.1			104.7								.1008	.0561	.0574
										19.1			107.6								.1008	.0561	.0590
				28,000						16.0	.33		105.0			.97	.957				.0990	.0551	.0575
				42,000						11.3	1.33		118.2			.93	1.011				.0610	.0344	.0432
										17.2			112.1								.0687	.0387	.0409
										17.2			113.3								.0687	.0387	.0414
										17.4			113.0								.0688	.0388	.0413
										20.9			110.6								.0686	.0387	.0404
										20.6			107.8								.0689	.0388	.0394
				42,000					18	20.7	1.33		104.3			.93	1.011				.0687	.0387	.0399
				14,000					17	11.7	.67		99.7			1.03	.984				.1729	.1051	.1093
										11.7			100.1								.1729	.1051	.1097
										12.1			101.7								.1749	.1063	.1115
										13.5			98 1								.1812	.1101	.1075
										13.9			94.7								.1827	.1110	.1038
										13.8			95.9								.1823	.1108	.1051
										16.0			103.4								.1890	.1149	.1133
										16.0			102.0								.1890	.1149	.1133
										16.1			103.8								.1892	.1150	.1138
										19.2			106.1								.1923	.1170	.1163
										19.1			106.6								.1923	.1169	.1168
				14,000						19.1	.67		107.3			1.03					.1923	.1169	.1176
				42,000						14.3	[illegible]		98.9			.93					.0660	.0362	.0361
										14.1			96.9								.0658	.0361	.0354
										14.4			101.6								.0662	.0363	.0371
										16.5			105.5								.0683	.0375	.0385
										16.3			105.2								.0681	.0374	.0384
										16.4			108.8								.0682	.0374	.0397
										20.9			105.7								.0686	.0376	.0386
										21.0			105.7								.0686	.0376	.0386
		Sheepsfoot Roller		42.000	2.79	11.0			17	20.8	.67		106.6			.93	.984				.0687	.0377	.0389
		Rubber Tire Roller		63,500	1.75	8.0			15	[illegible]	4		107.1			.81	1.117				.0227	.0117	.0118
										19.2	8		107.4				1.181				.0227	.0117	.0118
										14.2			99.6								.0216	.0112	.0110
Lean Clay	TM3-271	Rubber Tire Roller	0	63,500	1.75	8.0	75*	0.5	15	14.2	8	4.4	99.8	.456	1.0	.81	1.181	1.122	1.081	1.081	.0216	.0112	.0110

TABLE B-3. DENSITY DATA (CONTINUED)

*Assumed

SOIL TYPE	REFERENCE	COMPACTOR TYPE	[illegible]	W LB	R FT	b FT	c_o LB/FT^3	h_o FT	PI	w_o %	N	U FPS	[illegible] LB/FT^3	K	[illegible]F	W_F	N_F	C_F	n_F	R_F	[illegible]	PREDICTED [illegible] W/bh$_o$R	EXPERIMENTAL $\frac{\rho}{W/bh_oR}$
Lean Clay	TM3-271	Rubber Tire Roller	0	63,500	1.75	8.0	75*	0.5	15	14.4	8	4.4	101.[illegible]	.456	1.0	.81	1.181	1.083	1.061	1.090	.021[illegible]	.0112	.0112
										16.4			103.3								.0224	.0116	.0114
										16.4			104.0								.0224	.0116	.0115
										16.9			108.2								.0225	.0116	.0119
										17.6			103.2								.0227	.0117	.0114
										17.6			104.5								.0227	.0117	.0115
										17.6			105.9								.0227	.0117	.0117
										17.4			106.6								.0226	.0117	.0117
										17.4			108.1								.0226	.0117	.0119
										17.3			108.0								.0226	.0117	.0119
										20.0			107.0								.0227	.0117	.0118
										20.0			106.8								.0227	.0117	.0118
										20.2			107.8								.0227	.0117	.0119
										22.2			104.9								.0222	.0115	.0116
										22.6			105.1								.0221	.0114	.0116
										22.5	8		105.1				1.181				.0221	.0114	.0116
				63,500						19.0	16		108.5			.81	1.248				.0227	.0131	.0120
				100,000						17.5	4		110.9			.78	1.117				.0149	.0074	.0078
										17.0	8		111.5								.0148	.0074	.0078
										11.6			102.4								.0132	.0066	.0072
										11.9			101.0								.0133	.0066	.0071
										[illegible]1.7			101.5								.0132	.0066	.0071
										13.4			102.1								.0139	.0069	.0071
										13.4			102.2								.0139	.0069	.0071
										13.2			102.0								.0139	.0069	.0071
										16.7			108.2								.0148	.0074	.0076
										16.7			108.6								.0148	.0074	.0076
										16.0			108.9								.0147	.0073	.0076
										18.2			110.8								.0149	.0074	.0077
										18.3			110.7								.0149	.0074	.0077
										18.0			110.9								.0149	.0074	.0078
										18.6			110.0								.0149	.0074	.0077
										15.0			109.5				1.117				.0149	.0074	.0077
										18.9			110.6				1.181				.0149	.0078	.0077
										19.8			108.8								.0149	.0078	.0076
										20.0			109.0								.0149	.0078	.0076
										19.8			109.4								.0149	.0078	.0076
				100,000	1.75	8.0			15	16.9	8		111.7			.78	1.181	1.083	1.061		.0148	.0078	.0078
				125,000	1.54	7.0			17	16.0	4		113.0			.75	1.117	1.073	1.054		.0094	.0044	.0063
										15.4	8		115.2				1.181				.0093	.0046	.0064
										11.3			108.0								.0083	.0041	.0060
										12.8			111.0								.0087	.0043	.0062
										16.7			114.8								.0094	.0[illegible]47	.0064
										19.7	8		110.2				1.181				.0095	.0047	.0062
				125,000	1.54	7.0				14.7	16		116.6			.75	1.248	1.073	1.054		.0092	.0048	.0065
				100,000	1.75	8.0				12.0	8		101.4			.78	1.181	1.083	1.061		.0134	.0071	.0071
										12.3			101.7								.0135	.0071	.0071
										15.2			107.0								.0145	.0076	.0075
								0.5		20.3			105.3			.78			1.061		.0149	.0078	.0074
								1.0		10.5			96.0			.84			1.027		.0242	.0133	.0134
Lean Clay	TM3-271	Rubber Tire Roller	0	100,000	1.75	8.0	75*	1.0	17	12.7	8	4.4	101.3	.456	1.0	.84	1.181	1.083	1.027	1.090	.0260	.0143	.0142

TABLE B-3. DENSITY DATA (CONTINUED)

* Assumed

SOIL TYPE	REFERENCE	COMPACTOR TYPE	ω	W LB	R FT	b FT	ρ_o LB/FT^3	h_o FT	PI	μ_o %	N	U FPS	ρ LB/FT^3	K	ω_F	W_F	N_F	U_F	h_F	R_F	μ_F	PREDICTED $\frac{\rho}{W/bh_oR}$	EXPERIMENTAL $\frac{\rho}{W/bh_oR}$
Lean Clay	TM3-271	Rubber Tire Roller	0	100,000	1.75	8.0	75*	1.0	17	17.5	8	4.4	110.1	.456	1.0	.84	1.181	1.083	1.027	1.090	.0282	.0155	.0154
										20.0			103.5								.0283	.0155	.0145
										11.0			98.0								.0246	.0135	.0137
										13.5			99.9								.0266	.0146	.0140
								1.0		18.6			108.6			.84			1.027		.0284	.0156	.0152
								2.0		11.1			101.2			.90			.994		.0472	.0268	.0283
										14.1			105.1								.0153	.0292	.0294
										15.7			106.1								.0528	.0300	.0297
										20.3			104.1								.0538	.0306	.0291
										11.3			91.1								.0475	.0270	.0255
	TM3-271	Rubber Tire Roller	0	100,000	1.75	8.0		2.0	17	16.5	8	4.4	100.8		1.0	.90	1.181	1.083	.994	1.090	.0533	.0303	.0282
	TM3-271-10	Vibratory Roller- Towed (A)	168*	22,000*	2.0	5.0		1.0	23	12.2	4	4.4*	102.0	.456	.984	.99	1.165	1.094	1.033	1.054	.0769	.0474	.0464
										15.7			101.9				1.165				.0828	.0511	.0463
										21.4	4		103.0				1.165				.0837	.0516	.0468
										12.2	16		107.0				1.357				.0769	.0552	.0486
										17.8	16		110.3				1.357				.0845	.0607	.0501
		Vibratory Roller- Towed (A)	168*	22,000*	2.0	5.0				20.3	16		106.3		.984	.99	1.357	1.094	1.033	1.054	.0844	.0606	.0483
		Vibratory Roller- Towed (B)	377*	14,150*	1.25	4.5				13.3	4		98.7		.980	.98	1.165	1.056	1.010	1.076	.0699	.0410	.0392
										17.3	4		98.6				1.165				.0743	.0435	.0392
										20.7	4		103.4				1.165				.0743	.0435	.0411
										12.4	16		101.1				1.357				.0683	.0466	.0402
										17.0	16		107.4				1.357				.0742	.0507	.0427
		Vibratory Roller- Towed (B)	377*	14,150*	1.25	4.5				20.5	16		106.4		.980	.98	1.357			1.076	.0744	.0508	.0423
		Vibratory Roller- Self Prop (C)	147*	30,270*	1.58	7.0				13.8	4		93.1		.985	.98	1.165			1.013	.0654	.0363	.0340
										17.6	4		97.0				1.165				.0689	.0382	.0354
										21.9	4		99.8				1.165				.0679	.0377	.0365
										13.5	16		102.1				1.357				.0649	.0419	.0373
										17.8	16		107.0				1.357				.0689	.0445	.0391
		Vibratory Roller- Self Prop (C)	147*	30,270*	1.58	7.0				19.3	16		107.5		.985	.98	1.357		1.010	1.013	.0691	.0446	.0393
		Rubber Tire Roller (D)	0	100,000	1.75*	8.0				14.7	4		103.5		1.0	.87	1.165	1.083	1.027	1.090	.0273	.0153	.0145
										18.0	4		108.4				1.165				.0283	.0159	.0152
										20.5	4		106.0				1.165				.0282	.0158	.0148
										12.2	16		107.2				1.357				.0256	.0167	.0150
										16.8	16		109.8				1.357				.0281	.0183	.0154
	TM3-271-10	Rubber Tire Roller (D)			1.75*			1.0	23	19.8	16	4.4*	107.0	.457		.87	1.357				.0283	.0185	.0150
	TM3-271	Rubber Tire Roller		100,000	1.75	8.0		2.0	17	20.5	8	4.4	103.5	.456		.90	1.181	1.083	.994	1.090	.05377	.0305	.0290
				125,000	1.54	7.0		0.5		12.0			104.2			.75		1.073	1.054		.0085	.0042	.0045
										14.0			102.4								.0090	.0045	.0044
										17.0			103.4								.0095	.0047	.0044
								0.5		19.5			105.3			.75			1.054		.0095	.0047	.0045
								1.0		11.9			100.5			.80			1.205		.0162	.0083	.0087
										14.8			103.9								.0174	.0089	.0090
										16.5			110.9								.0179	.0092	.0096
										19.6			106.5								.0181	.0093	.0092
										12.4			102.7								.0164	.0084	.0088
										16.4			109.2								.0179	.0092	.0094
										17.9			107.1								.0181	.0093	.0092
Lean Clay	TM3-271	Rubber Tire Roller	0	125,000	1.54	7.0	75*	1.0	17	19.3	8	4.4	106.9	.456	1.0	.80	1.181	1.073	1.205	1.090	.0181	.0093	.0092

TABLE B-3. DENSITY DATA (CONTINUED)

*Assumed

SOIL TYPE	REFERENCE	COMPACTOR TYPE	ω	W LB	R FT	b FT	γ_o LB/FT³	h_o FT	PI	w_o %	N	U FPS	γ LB/FT³	K	ω_F	W_F	N_F	U_F	h_F	R_F	γ_F	PREDICTED $\bar{W}/bh_oR$	EXPERIMENTAL $\bar{W}/bh_oR$
Lean Clay	TM3-271	Rubber Tire Roller	0	125,000	1.54	7.0	75*	2.0	17	15.2	8	4.4	100.4	.456	1.0	.86	1.181	1.073	.988	1.090	.0334	.0179	.0173
										16.4			111.1								.0339	.0181	.0192
										18.5			108.7								.0344	.0184	.0187
										10.1			99.9								.0289	.0155	.0172
										14.2			104.8								.0328	.0175	.0181
										16.1			110.2								.0388	.0181	.0190
	TM3-271	Rubber Tire Roller	0	125,000	1.54	7.0	75*	2.0	17	18.9	8	4.4	107.8			.86	1.181	1.073	.988	1.090	.0344	.0184	.0190
	MP 4-127	Impact Compactor	105	10,000	2.5	2	75	.83	15	13.8	6	.73	110.5			1.08	1.218	1.113	1.053	.987	.0736	.0504	.0458
			105	10,000				.50		12.5	3	.73	114.6			1.02	1.128		1.079	.949	.0233	.0137	.0143
			98	35,600		2		.58		13.7	3	1.83	111.4			.89			1.071	.987	.0161	.0086	.0091
			98	28,500				.58		14.0	3	1.83	110.7			.90					.0200	.0106	.0113
			98	21,400				.58		14.4	3	1.83	110.2			.91	1.128				.0263	.0143	.0149
			98	28,500				.58		13.0	6	.73	113.4			.90	1.218		1.071		.0195	.0113	.0115
			98	21,400		2		.62		12.7	3	.73	113.3			.91	1.128		1.067	.987	.0269	.0157	.0164
Lean Clay	MP 4-127	Impact Compactor	44	7,300	2.5	1		.58	15	13.2	6	.73	112.6	.456		.93	1.218	1.113	1.071	.949	.0365	.0210	.0224
Clayey Sand	TM3-271-1	Sheepsfoot Roller	0	14,000	2.79	11.0		.5	2	12.7	.5	4.4	115.3	.725		1.00	.996	1.000	1.084	1.081	.1535	.1299	.1264
		Sheepsfoot Roller		25,200	2.79	11.0		.5		12.4	.5		113.5				.996				.0847	.0717	.0713
		Tractor		34,500	4.75*	3.67		.5		13.5	3		113.0				1.005				.0360	.0287	.0285
		Tandem RT Roller		80,000	4.95	4.0*		.5		12.2	8		116.0				1.010				.0171	.0138	.0143
				160,000	4.95	4.0		.5		12.2	8		116.2				1.010				.0086	.0069	.0072
Clayey Sand	TM3-271-1	Tandem RT Roller	0	160,000	4.95	4.0	75	.5	2	12.2	16	4.4	116.0	.725	1.0	1.00	1.014	1.000	1.084	1.081	.0086	.0070	.0072
Sand	TM3-271-10	Vibratory Roller- Towed (A)	168*	22,000*	2.0	5.0	90*	2.0	0	7.2	4	4.4*	109.0	.612	0	1.00	1.168	.901	1.000	1.054	.1197	.0812	.0991
										10.6			103.8								.1351	.0917	.0944
										12.4	4		104.5				1.168				.1421	.0964	.0950
										5.6	8		98.6				1.262				.1117	.0819	.0896
										11.3			96.8								.1379	.1011	.0880
										13.5	8		102.9				1.262				.1460	.1070	.0935
										6.6	16		102.1				1.364				.1167	.0925	.0928
										6.9			104.5								.1182	.0936	.0950
		Vibratory Roller- Towed (A)	168*	22,000*	2.0	5.0				7.8	16		103.0				1.364	.901	1.000	1.054	.1226	.0971	.0954
		Vibratory Roller- Towed (B)	377*	14,150*	1.25	4.5				9.5	4		96.5				1.168	1.006	.978	1.076	.1140	.0805	.0767
										10.0			102.5								.1159	.0818	.0815
										9.9	4		106.3				1.168				.1155	.0815	.0845
										4.1	8		94.0				1.262				.0909	.0693	.0747
										6.8			94.3								.1030	.0785	.0750
										12.6	8		103.9				1.262				.1249	.0952	.0826
										4.2	16		102.7				1.364				.0914	.0753	.0816
										5.5			104.4								.0973	.0802	.0830
		Vibratory Roller- Towed (B)	377*	14,150*	1.25	4.5				7.3	16		113.0				1.364	1.006	.978	1.076	.1051	.0866	.0898
		Vibratory Roller- Self Prop (C)	147*	30,270*	1.58	7.0				4.8	4		102.6				1.168	1.007	.987	1.092	.0865	.0612	.0750
										9.3			101.2								.1041	.0736	.0739
										12.0	4		105.8				1.168				.1130	.0799	.0773
										6.3	8		100.1				1.262				.0926	.0708	.0731
										8.1			95.0								.0997	.0762	.0694
										11.0	8		103.4				1.262				.1099	.0840	.075[illegible]
										5.4	16		107.0				1.364				.0890	.0735	[illegible]
										6.1			104.9								.0918	.0758	.0766
		Vibratory Roller- Self Prop (C)	147*	30,270*	1.58	7.0				8.8	16		116.3				1.364	1.007	.986	1.092	.1023	.0845	.0850
Sand	TM3-271-10	Rubber Tire Roller (D)	0	100,000	1.75*	8.0	90*	2.0	0	6.6	4	4.4*	99.2	.612	0	1.00	1.168	1.008	.994	1.090	.0360	.0254	.0273

TABLE B-3. DENSITY DATA (CONTINUED)

*Assumed

SOIL TYPE	REFERENCE	COMPACTOR TYPE	ω	W LB	R FT	b FT	ρ_o LB/FT^3	h_o FT	PI	μ_o %	N	U FPS	ρ LB/FT^3	K	ω_F	W_F	N_F	U_F	h_F	R_F	~F	PREDICTED $\frac{\rho}{W/bh_oR}$	EXPERIMENTAL $\frac{\rho}{W/bh_oR}$
Sand	TM3-271-10	Rubber Tire Roller (D)	0	100,000	1.75*	8.0	90*	2.0	0	-	4	4.4*	-	.612	0	1.00	-	1.008	.994	1.090	.0360	.0254	-
										-	4		-				-						-
										5.0	8		102.4				1.262				.0345	.0263	.0287
										7.8			98.9								.0377	.0287	.0277
										9.1	8		110.2				1.262				.0396	.0302	.0308
										5.9	16		100.3				1.364				.0349	.0288	.0281
										6.9			105.4								.0364	.0300	.0295
Sand		Rubber Tire Roller (D)	0	100,000	1.75*	8.0	90*	2.0	0	9.9	16	4.4*	104.7	.612	0		1.364	1.008	.994	1.090	.0407	.0335	.0293
Limestone 1-1/2" Max		Vibratory Roller-Towed (A)	168*	22,000*	2.0	5.0	132*	1.0	0	3.4	4	4.4	133.5	.914	1.0		1.025	1.010	1.033	1.054	.0602	.0620	.0607
										7.3	4		133.7				1.025				.0602	.0620	.0608
										9.9	4		137.8				1.025				.0601	10619	.0626
										3.0	8		135.8				1.038				.0601	.0627	.0617
										7.1	8		135.6				1.038				.0602	.0628	.0616
										9.1	8		141.0				1.038				.0601	.0627	.0641
										2.7	16		140.4				1.051				.0601	10634	.0638
										7.1	16		138.9				1.051				.0602	.0635	.0631
		Vibratory Roller-Towed (A)	168*	22,000*	2.0	5.0				8.7	16		143.0				1.051	1.010	1.033	1.054	.0602	.0635	.0650
		Vibratory Roller-Towed (B)	377*	14,150*	1.25	4.5				2.9	4		136.6				1.025	1.006	1.010	1.076	.0526	.0539	.0543
										5.6	4		135.1				1.025					.0539	.0537
										7.8	4		137.8				1.025					.0539	.0548
										3.1	8		135.6				1.038					.0546	.0539
										5.1	8		135.5				1.038					.0546	.0539
										7.7	8		136.4				1.038					.0546	.0542
										3.3	16		137.4				1.051					.0555	.0546
										5.6	16		135.9				1.051					.0555	.0540
		Vibratory Roller-Towed (B)	377*	14,150*	1.25	4.5				8.0	16		137.4				1.051	1.006	1.010	1.076	.0526	.0555	.0546
		Vibratory Roller-Self Prop (C)	147*	30,270*	1.58	7.0				2.6	4		137.2				1.025	1.008	1.022	1.088	.0483	.0507	.0501
										6.6	4		135.7				1.025					.0507	.0496
										8.1	4		136.9				1.025					.0507	.0500
										2.7	8		138.1				1.038					.0514	.0504
										6.8	8		134.5				1.038					.0514	.0491
										7.8	8		137.8				1.038					.0514	.0503
										3.0	16		140.2				1.050					.0520	.0512
										6.5	16		142.1				1.051					.0520	.0519
		Vibratory Roller Self Prop (C)	147*	30,270*	1.58	7.0				8.4	16		140.2				1.051	1.008	1.022	1.088	.0483	.0520	.0512
		Rubber Tire Roller (D)	0	100,000	1.75*	8.0				2.6	4		132.8				1.025	1.009	1.027	1.090	.0185	.0196	.0186
										7.5	4		136.0				1.025					.0196	.0190
										9.2	4		139.6				1.025					.0196	.0195
										2.6	8		134.1				1.038					.0198	.0188
										7.2	8		135.4				1.038					.0198	.0190
										8.8	8		141.3				1.038					.0198	.0198
										2.6	16		136.1				1.051					.0201	.0190
										7.4	16		137.0				1.051					.0201	.0192
Limestone 1-1/2" Max	TM3-271-10	Rubber Tire Roller (D)			1.75*			1.0		8.6	16		143.7				1.051	1.009	1.027	1.090	.0185	.0201	.0201
Crushed Limestone 1-1/2"	TM3-271	Rubber Tire Roller	0	100,000	1.75	8.0	132*	.33	0	2.3	32	4.4	142.6	.914	1.0	1.00	1.064	1.008	1.081	1.090	.0061	.0071	.0066
										2.6	32		143.3						1.081	1.090	.0061	.0071	.0066
	TM3-271	Rubber Tire Roller	0	100,000	1.75	8.0	132*	.33	0	3.8	32	4.4	150.3	.914	1.0	1.00	1.064	1.008	1.081	1.090	.0061	.0071	.0069

TABLE B-3. DENSITY DATA (CONTINUED)

*Assumed

SOIL TYPE	REFERENCE	COMPACTOR TYPE	ω	W LB	R FT	b FT	ρ_o LB/FT^3	h_o FT	PI	ω_o %	N	U FPS	ρ LB/FT^3	K	ω_F	W_F	N_F	U_F	h_F	R_F	ν_F	PREDICTED $\frac{\rho}{W/bh_oR}$	EXPERIMENTAL $\frac{\rho}{W/bh_oR}$
Crushed Limestone 3/4"	TM3-271	Rubber Tire Roller	0	120,000	1.54	7.0	132*	0.33	0	1.3	8	4.4	139.1	.914	1.0	1.00	1.038	1.075	1.075	1.090	.0039	.0044	.0041
										3.2			146.8								.0039	.0044	.0043
										3.9			149.8								.0039	.0044	.0044
										5.8	8		146.0				1.038				.0039	.0044	.0043
										1.4	16		140.3				1.051				.0039	.0044	.0042
										2.3			147.5									.0044	.0044
										2.6			148.7									.0044	.0044
										4.9	16		149.1				1.051					.0044	.0044
										1.7	32		142.6				1.064					.0045	.0042
										3.8			152.6									.0045	.0045
3/4" 1-1/2"										4.3			150.2									.0045	.0044
										5.1	32		148.3				1.064					.0045	.0044
										1.3	8		136.2				1.038					.0044	.0040
										2.8			140.8									.0044	.0042
										4.7			147.7									.0044	.0044
										6.6	8		143.2				1.038					.0044	.0042
										1.2	16		137.1				1.051					.0044	.0041
										2.7			141.1									.0044	.0042
										4.6			149.1									.0044	.0044
										7.0	16		142.0				1.051					.0044	.0042
										1.2	32		141.6				1.064					.0045	.0042
Crushed Limestone 1-1/2"										1.8			146.0									.0045	.0043
										3.5			151.2									.0045	.0045
				120,000	1.54	7.0				6.1	32		144.8				1.064	1.075	1.075	1.090	.0039	.0045	.0043
Crushed Limestone 3/4"				100,000	1.75	8.0				0.9	8		145.1				1.038	1.008	1.081	1.090	.0060	.0069	.0067
										1.9			139.6									.0069	.0064
										3.6			146.0									.0069	.0067
										4.0			146.7									.0069	.0068
										4.8	8		148.0				1.038					.0069	.0068
										0.9	16		146.8				1.051					.0070	.0068
										2.5			141.6									.0070	.0065
										3.6			146.0									.0070	.0067
										3.8			149.9									.0070	.0069
										4.6	16		151.4				1.051					.0070	.0070
										0.7	24		146.5				1.059					.0070	.0068
										1.7			143.7									.0070	.0066
										2.9			146.4									.0070	.0068
										3.6			152.3									.0070	.0070
										4.1	24		154.3				1.059					.0070	.0071
										0.6	32		146.1				1.064					.0071	.0067
										1.8			145.3									.0071	.0067
										2.4			147.9									.0071	.0068
3/4" 1-1/2"										3.1			153.6									.0071	.0071
										3.6	32		154.9				1.064					.0071	.0071
										0.4	8		142.4				1.038					.0069	.0066
										1.9			135.7									.0069	.0063
										3.3			137.2									.0069	.0063
										3.5			137.5									.0069	.0063
										3.9	8		147.7				1.038					.0069	.0068
										0.5	16		144.9				1.051					.0070	.0067
										2.2			137.2									.0070	.0063
1-1/2"	TM3-271	Rubber Tire Roller	0	100,000	1.75	8.0	132*	.33	0	3.4	16	4.4	138.4	.914	1.0	1.00	1.051	1.008	1.081	1.090	.0060	.0070	.0064

TABLE B-3. DENSITY DATA (CONCLUDED)

SOIL TYPE	REFERENCE	COMPACTOR TYPE	ω	W LB	R FT	b FT	γ_o LB/FT³	h_o FT	PI	w_o %	N	U FPS	γ LB/FT³
Crushed Limestone 1-1/2"	TM3-271	Rubber Tire Roller	0	100,000	1.75	8.0	132*	.33	0	3.4	16	4.4	140.9
										3.8	16		147.6
										0.5	24		146.5
										1.7			137.8
										2.9			140.9
										3.3			143.0
										3.7	24		149.3
										0.3	32		147.4
Crushed Limestone 1-1/2"	TM3-271	Rubber Tire Roller	0	100,000	1.75	8.0	132*	.33	0	1.6	32	4.4	137.7

SOIL TYPE	K	ω_F	W_F	N_F	U_F	h_F	R_F	μ_F	PREDICTED $\frac{\rho}{W/bh_oR}$	EXPERIMENTAL $\frac{\rho}{W/bh_oR}$
Crushed Limestone 1-1/2"	.914	1.0	1.00	1.051	1.008	1.081	1.090	.0061	.0070	.0069
				1.051					.0070	.0068
				1.059					.0070	.0068
									.0070	.0064
									.0070	.0066
									.0070	.0066
				1.059					.0070	.0069
				1.064					.0071	.0068
Crushed Limestone 1-1/2"	.914	1.0	1.00	1.064	1.008	1.081	1.090	.0061	.0071	.0064

*Assumed

TABLE B-4. APPROXIMATE ERROR OF DENSITY MODEL, PERCENT

Soil Type	Type of Compactor: Rubber Tired Roller	Vibratory Compactor	Sheeps-Foot Roller	Tractor
Lean Clay	5.3	10.0	4.5	ND
Clayey Sand	3.5	ND	1.7	0.7
Sand	4.6	6.2	ND	ND
Crushed Limestone	4.1	1.6	ND	ND
Overall	4.7	5.9	4.4	0.7

ND = No Data

controlled set of compaction experiments could be conducted, it is reasonable to expect that a representative compaction model could be formulated.

Figure B-7 through B-10 compare the density factor predicted to the experimental density factor for the four soil types. The vibratory compactor appears to give a consistently higher compaction density factor than does the rubber-tired roller, and the sheepsfoot roller gives the highest density factor for lean clay and clayey sand.

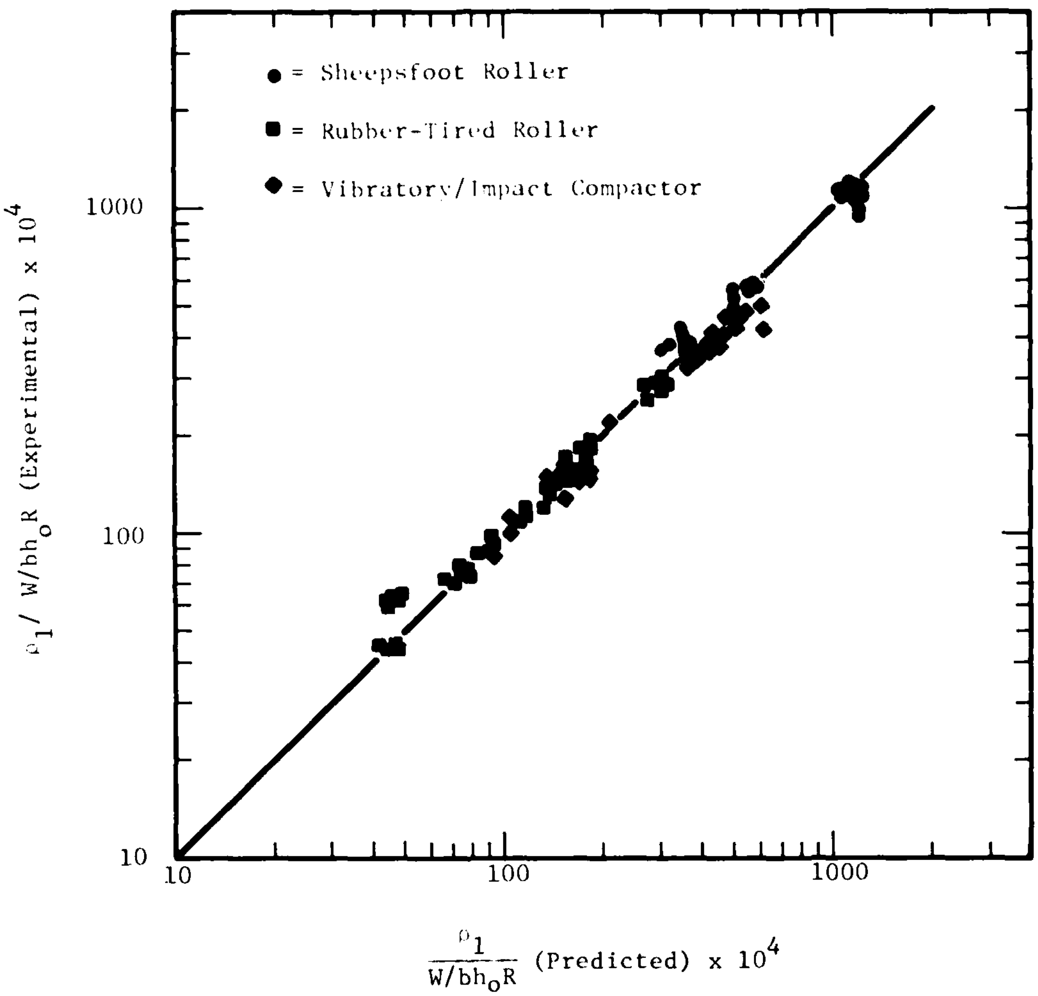


Figure B-7. Experimental Density Factor Versus Predicted Density Factor - Lean Clay

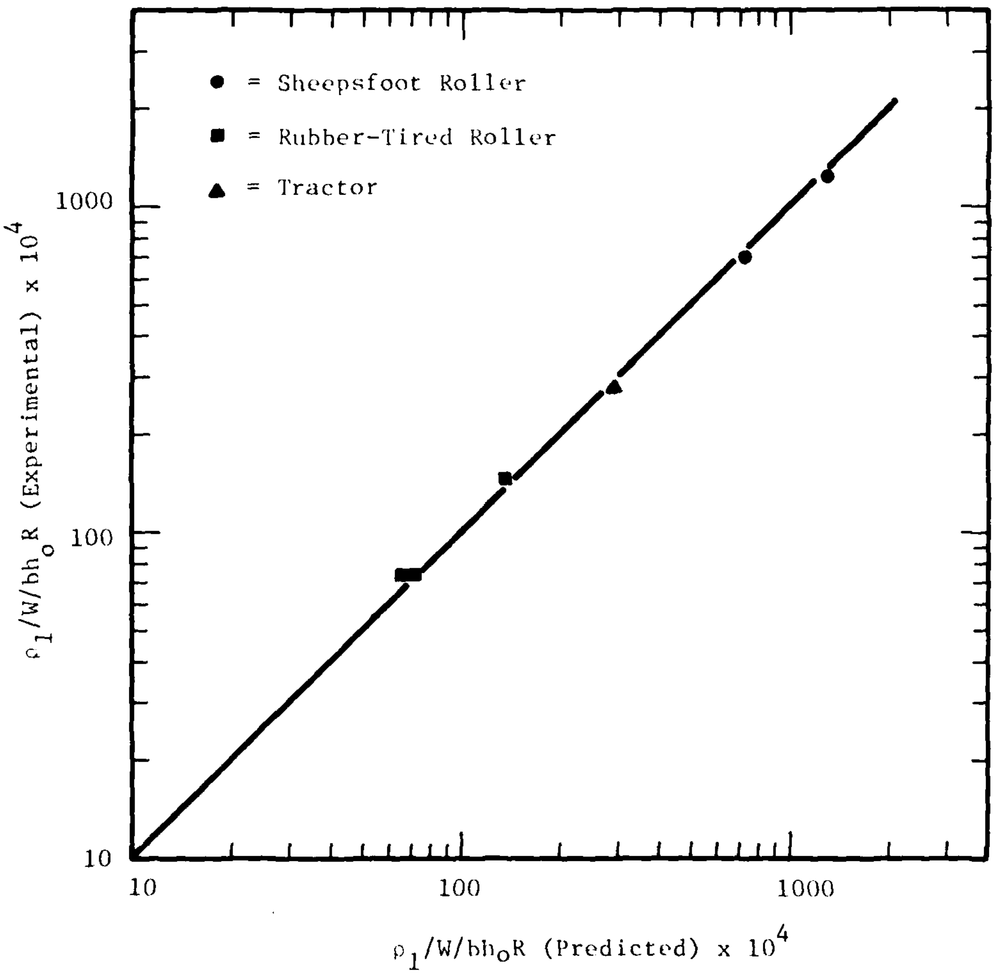


Figure B-8. Experimental Density Factor Versus Predicted Density Factor - Clayey Sand

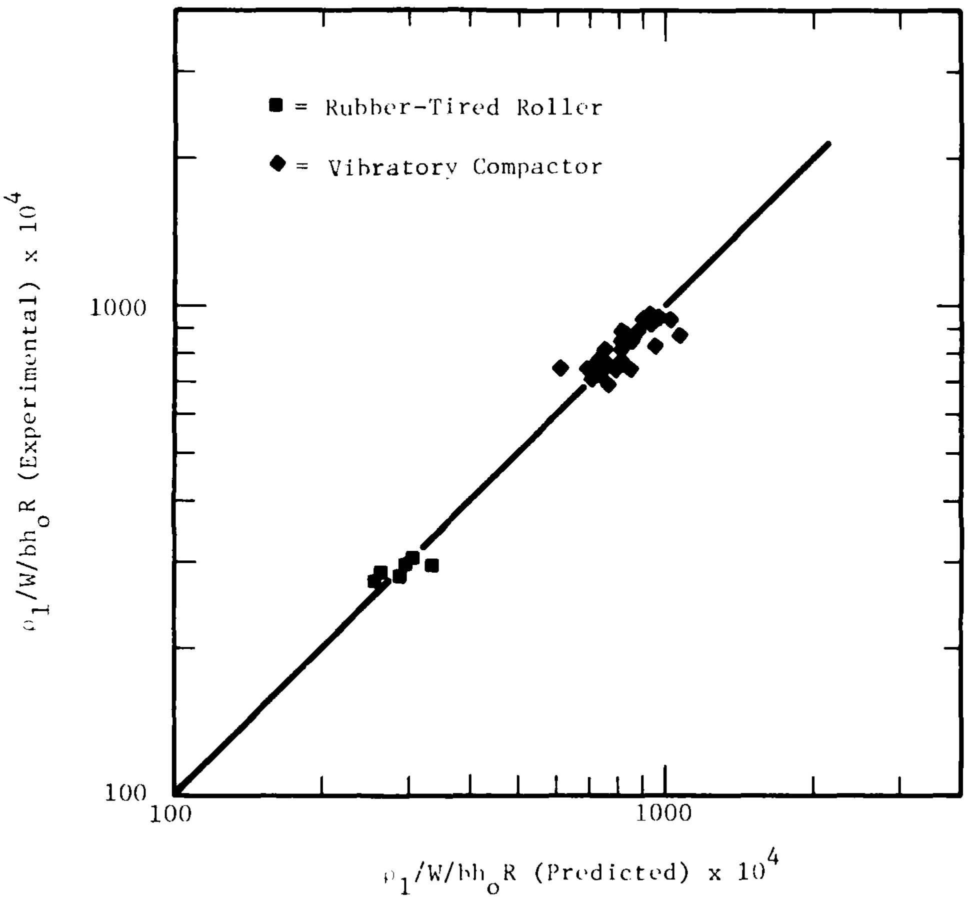


Figure B-9. Experimental Density Factor Versus Predicted Density Factor - Sand

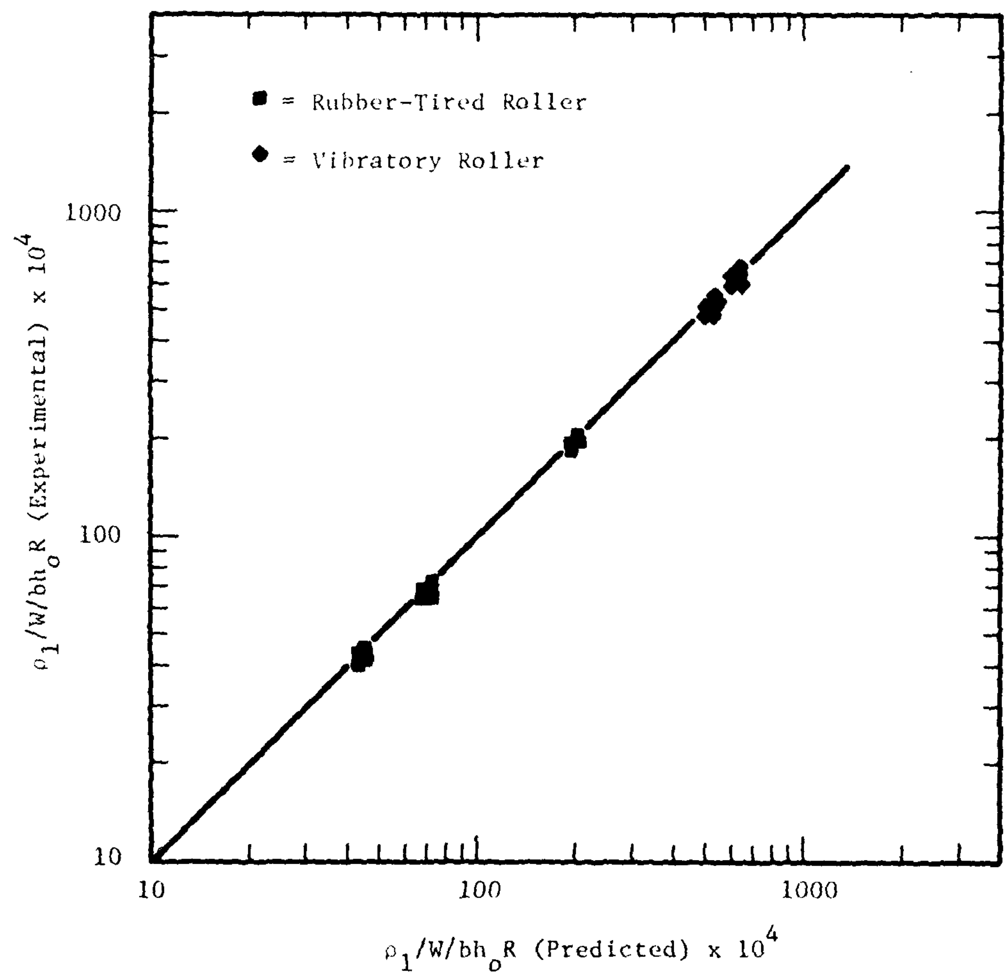


Figure B-10. Experimental Density Factor Versus Predicted Density Factor - Crushed Limestone

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B-9. Hall, J. W., "Soil Compaction Investigation, Report No. 10, Evaluation of Vibratory Rollers on Three Types of Soils," TM3-271, Waterways Experiment Station, March 1968.

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APPENDIX C

MATERIALS

INORGANIC MATERIALS

- The source is natural minerals or calcined mineral mixtures in hydrated and anhydrous states.
- The densities are usually between 100 and 150 lb/ft^3.
- The advantages of inorganic materials are as follows:
  - Low cost
  - High degree of stability
  - Low toxicity
  - Non-flammable
  - Broad tolerance in mixing
  - Simple requirements for mixing, proportioning, and delivery equipment
  - Equipment and personnel are easily cleaned
  - Water based
  - Compatible with most organic and inorganic aggregates and fillers
  - Curing rates and setting rates are variable
  - Moderate to low cure exotherm
  - Good final properties even though cured over large temperature range
  - Many candidate inorganic materials have good chemical resistance
  - Low shrinkage in the order of 0 to 1% and some are slightly expansive
  - Excellent to moderate weathering properties
  - Available in consistent quality in most parts of the world
- The disadvantages of inorganic materials are as follows:
  - Very sensitive to moisture in storage
  - Adhesive properties only fair and must be supplemented in many inorganics

- Low tensile and flexural strength which require reinforcement in most cases
- Strength inversely proportioned to fluidity or water concentration, i.e., water/solids ratios
- Brittle inelastic products
- Limited control of cure rate
- Dependent upon water content for fluidity and cure
- Requires moderate temperature or application of heat to obtain cure
- High freezing point due to water content.

TABLE C-1. RAPID SETTING CEMENTS

- Special formulations based on portland cement or other compositions
- Set time - variable, from 3 minutes up
- Bulk density - set, neat, 135-145 lb/ft^3
- Strength - compressive, 1000+ psi in 1-1/2 to 2 hr
- Cost - about \$.06 - \$.08/lb (\$220 - \$300/yd^3)
- Shelf life short, however it could be several years in sealed containers
- Mixed with aggregate and water, same as portland cement; set time generally slower at low temperatures
- Not widely available

TABLE C-2. GYPSUM CEMENTS

- Formulated for various applications; one formula - Duracal® from U.S. Gypsum was developed for BDR use
- Set time - normally 20 to 35 min depending on formulation
- Mixed material must be kep above 32°F during curing stage
- Compressive strength - 1 hr after set, neat between 1500 and 6000 psi
- Shrinkage - none; has slight setting expansion
- Density (wet) - 130-145 lb/ft^3, neat, set material
- Cost - \$.05 - \$.08/lb (\$175 - \$300/yd^3)
- Shelf life - several years in sealed containers
- Is mixed with water in ratios of 0.26 to 0.45 water/cement to form pourable slurry, warm water accelerates set as do certain inorganic salts; can be reinforced with glass fibers

TABLE C-3. VERY HIGH EARLY (VHE) CEMENT

- A new proprietary cement under development by U.S. Gypsum
- Hypothesis - a combination of gypsum and portland cement and calcium
- Very little data exists and none found in literature
- Reportedly had excellent high early strength, long shelf life, easy to mix, safe, available, and less expensive than polymers
- USG reports they have a pilot production lot of 500 tons for testing

TABLE C-4. FAST SETTING CONCRETE - SET 45®

- A one-component concrete based on magnesium phosphate requiring only water and mixing in order to use
- Solids: water ratio 6:1; cementation based on exothermic chemical reaction (140°F)
- Bulk density - 138 lb/ft^3, plastic condition
- With warm mixing water can be used at 0°F
- Gives excellent bond with extending aggregate and surface to which applied
- Compressive strength - 1975 psi in 45 min
- Flexural strength - 825 psi in 3 hr
- Expansion/contraction similar to portland cement concrete
- Shelf life - typically about 6 mos; can be extended if sealed
- Cost - $\$450/yd^3$ with aggregate
- Available through Set Products, Macedonia, Ohio

TABLE C-5. FLY ASH

- Available from many coal-fired power plants
- Self-hardening type set time - 6 to 30 minutes with water/ash ratio of 0.3 to 0.5
- Bulk density - self-hardening type, after set - 120 to 130 lb/ft^3
- Compressive strength - 500 to 1000 psi an hour after setting, increasing to over 2000 psi when dry
- Cost - \$1-\$10/ton (\$2-\$15/yd^3)
- Shelf life - At least several years for self-hardening type under protective cover; indefinite for non-hardening type
- Little to no shrinkage on curing (self-hardening)
- Can be extended with sand and aggregate
- Mixed and placed with high capacity jet slurrier or other equipment

TABLE C-6. GYPSUM PLASTER

- Fast setting calcined gypsum
- Set time - controllable, from 5 min upward at about 40 to 70°F
- Bulk density - 100 to 112 lb/ft^3, dry
- Compressive strength - 1500-2500 psi, set, dry
- Cost - \$.025 - \$.03/lb (\$70 - \$90/yd^3)
- Shelf life - several years in sealed containers
- Can be mixed dry with sand and stored and then with water when used
- Develops moderate exotherm on setting; can be continuously mixed
- Can be reinforced with glass fibers

TABLE C-7. SULFUR

- Must be melted for use in BDR unless employed in lump form as aggregate
- Bulk density - lump 80-85 lb/ft^3, solid 125 lb/ft^3
- Compressive strength - similar to portland cement concrete, about 5000 psi
- Cost - \$60 to \$65/yd^3 (FRASCH), lower for sour gas sulfur
- Solidifies quickly on cooling from molten state (melts at 246°F)
- Can be melted with included fine aggregate
- Shelf life - indefinite
- Combustible, but can be rendered self-extinguishing; cannot be applied molten on wet surfaces
- Widely available

TABLE C-8. INORGANIC SPHERES (LIGHTWEIGHT AGGREGATE)

- Inert, made from clay, shale, slate or pelletized, sintened fly ash
- Bulk density - 25 to 60 lb/ft^3, loose, 1/8" to 1/2" size
- Commonly used as concrete aggregate to produce concrete of 90 to 120 lb/ft^3; can be used as aggregate in polymers and resins
- Shelf life - indefinite
- Compressive strength - individual spheres, usually above 1000 psi
- Cost - \$20 to \$25/yd^3
- Available in North American and some European countries

ORGANIC MATERIALS

- Properties:
  - Source: Fossil fuels, plants, animals
  - Density, 50-80 lb/ft^3
  - Compressive strength, 3,000-20,000 psi
  - Flexural strength, 5,000-20,000 psi
  - Shrinkage, 0-10% volumetric
  - Environmental effects after cure, poor-excellent
  - Service temperature, (-40°F)-(200°F)
  - Chemical resistance, poor-excellent
  - Cost, $.30 - several $/lb
- The advantages of organic materials are as follows:
  - Generally fast setting; variable rate
  - High early strength
  - Good adhesion to various substrates
  - Excellent weathering properties
  - Some have virtually no shrinkage when filled
  - Good chemical resistance
  - Low viscosity (self-leveling)
  - Accepts fillers readily
  - Good final properties over large temperature range
  - Easily repairable
  - Suitable for all size craters
  - Good compressive, flexural and impact strengths
  - Can be applied at temperature between -25 and 125°F

- Disadvantages
  - Relatively short shelf life
  - Generally multi-component systems
  - The need for special mixers that are high speed yet capable of controlling mixing ration to within a few percent
  - Storage of large masses of several components
  - Safety-toxic, fire, explosive and OSHA requirements
  - Possible inhibition of cure by some foreign materials
  - Environmental effect on cure, time and strength
  - High cost
  - High exotherm in large masses
  - Disposal of out-of-date material
  - Very little data exists with industrial companies for the use of large quantities of catalyzed polymer
  - Some have high shrinkage
  - Suppliers caution against accelerated cures

TABLE C-9. AMINOS (UREA, MELAMINE/FORMALDEHYDE, ETC)

- Source - Petrochemical
- Cost - \$.25 - \$.75/lb
- Cured was an acidic catalyst
- Cure rate ranges from instantaneous to several hours
- Moderately low exotherm
- Filler compatibility - good except with alkaline fillers which reacts with catalyst and stops the reaction
- Compressive strength - moderate (over 1000 psi in hour)
- Shrinkage - High in the unfilled state; however, this may be controlled with fillers
- Density - 50-70 lb/ft^3
- Mixing - the materials water soluble, catalyst to be added on site. For best results the material should be combined with a high shear mixer.
- Storage - should be stored in a controlled environment to extend shelf life beyond 1 year

TABLE C-10. EPOXY

- Source - synthetic and petrochemical source
- Cost - between $0.80 and $2.00 per pound
- Mechanism of cure - amine, BF_3 or other cationic agents
- Rate of cure - may be controlled to be between a few seconds to many hours
- Exotherm - higher than most other thermosetting polymers. The amount of exotherm is proportional to the rate of reaction.
- Filler compatibility - good
- Compressive strength - high; over 5,000 psi in flexure upon hardening
- Shrinkage - moderate, may have as high as 2% linear in fast curing, unfilled systems
- Density - 50-70 lb/ft^3 unfilled
- Mixing - catalyst added on site with high shear mixer. The proportions are very critical.
- Storage - limited storage stabilities (1-2 years)

TABLE C-11. METHYL METHACRYLATE AND RELATED ACRYLICS (SODIUM AND CALCIUM ACRYLATES)

- Source - petrochemical
- Cost - \$0.60 to \$1.50/lb
- Mechanism of cure - peroxide plus amine accelerator with crosslinking agents
- Rate of cure - from minutes to hours
- Exotherm - varies with rate -- very high compared to polyester
- Filler compatibility - good
- Compressive strength - high (2,000-5,000 psi, cured)
- Shrinkage - varies with rate of exotherm (1-2% linear at high rate of cure)
- Density - 50-70 lb/ft^3
- Mixing - critical proportions, mixed on site
- Storage - good storage stability with inhibitor. 1-3 years may be obtained under proper conditions.

TABLE C-12. CASTABLE NYLON

- Monomer cast system plus catalyst for polymerization
- Compressive strength 3,000 psi in 1 hr
- Cure time - 1 hr
- Flexural strength - 7,000 psi
- Special patented process and equipment
- Highly technical personnel required to operate equipment
- Equipment not portable as presently designed
- Presently Polymer Corp. operates a system under license from Monsanto

TABLE C-13. PHENOLIC

- Source - petrochemical - coal
- Cost - \$0.40 to \$0.75/ lb
- Mechanism of cure - acid catalyst; amine catalyst--depending upon system
- Rate of cure - varies with concentration and strength of hardener
- Exotherm - moderate at high rate of cure unfilled
- Filler compatibility - good
- Strength - 5-10,000 psi compressive, unfilled
- Shrinkage - moderate, unfilled; low with filler
- Density - 50-70 lb/ft^3
- Mixing - Add catalyst on site with good shear mixing equipment
- Storage - good stability if catalyst excluded

TABLE C-14. POLYESTER

- Source - petrochemical synthetic
- Cost - \$.40 - \$.60/lb (neat)
- Mechanism of cure - peroxide catalyst, metal soap accelerator, or amine accelerator
- Rate of cure - 10 minutes to hours
- Exotherm (in mass) - high but less than epoxy and urethanes
- Filler compatibility - good
- Strength - high early; several thousand psi ultimate compressive strength
- Shrinkage - variable with exotherm and filler
- Density - 50-70 lb/ft^3
- Mixing - critical proportions, mixed on site
- Storage - limited storage stability (1-2 yr) unless loaded with retardants and sealed well

TABLE C-15. POLYESTER POLYMER (SPECIAL)

- Developed by NCEL, Dow Chemical and PPG Industries
- Flexural strength (fiber glass reinforced) - 40,000 psi
- Cure time - instantaneous to 90 minutes; typically 10-20 minutes
- Shelf life - 5 years
- Compatible with wet environment
- Low exotherm when mixed with aggregate (75% - 25% resin)
- Recommended storage temperature - 75°F or below
- Tested for uses as helicopter landing pad over varying base materials
- Strengths, shelf life, moisture compatibility, and other properties verified in field tests using fiber glass reinforcement

TABLE C-16. WATER EXTENDED POLYESTER (WEP)

- Source - petrochemical and vegetable
- Cost - $0.40 to $0.60/lb (neat)
- Mechanism of cure - peroxide catalyst, metal soap accelerator or amine accelerator
- Rate of cure - 10 minutes to hours
- Exotherm (in mass) - high but less than epoxy and urethanes
- Filler compatibility - good
- Strength - high early; several thousand psi ultimate compressive
- Shrinkage - extreme with warping and exudation
- Density - 50-70 lb/ft^3
- Mixing - difficult to emulsify uniformly and maintain emulsion
- Storage - limited storage stability (1-2 yr) unless loaded with retardants and sealed well

TABLE C-17. URETHANE ELASTOMER

- Petrochemical source
- Method of cure - isocyanates + polyols
- Rate of hardening - minutes to hours
- Exotherm - moderate to high but should not result in detrimental effect
- Filler compatibility - good
- Strength - 15,000-20,000 flexural
- Shrinkage - moderate (less than 2% lineal, unfilled)
- Specific gravity - .9 - 1.2
- Cost - $0.40 to $0.80/lb
- Mixing - components mixed on site with high shear mixer
- Storage - must be in controlled environment for shelf life in excess of 1 year

TABLE C-18. INSTANT SET POLYMER (ISP) URETHANE

- Two component system manufactured by Dow Chemical
- Cure time - projected to be 15 minutes, but currently 1 minute
- Shelf life unknown as yet but should be > 1 yr
- Shrinkage with aggregate approximately 1%
- Compressive strength - 9,200 psi
- Flexural strength - 13,200 psi
- Organic material added to act as heat sink and reduce exotherm
- Specific gravity - 1.16
- Cost - $.70/lb
- May be developed to combine with water to produce a graded density foam

TABLE C-19. POLYURETHANE FOAM

- Petrochemical - coal source
- Method of cure - isocyanates, polyols copolymerization
- Rate of hardening - seconds to hours
- Exotherm - relatively high because of insulating properties of foam
- Filler compatibility - best with fiber glass; only fair with other materials
- Strength - 15 to 4,000 psi compressive
- Density - 1.3 - 40 lb/ft^3
- Cost - $0.40 to $0.80/lb of resin
- Mixing and storage - components mixed on site with high shear mixer and dispensed. Storage life 1-2 yr with precautions.

TABLE C-20. REINFORCED POLYESTER FOAM

- Two component, rigid thermosetting fiberglass reinforced foam
- Flexural strength - 7,000 psi
- Cure time - 5-minute gel, 30-minute cure
- Density - 30-40 lb/ft^3
- Cost - <$1/lb
- May be applied using current fiberglass spray equipment
- The catalyst used with this material is part of the foaming agent and is safet than the usual peroxide catalysts
- Shrinkage - nil
- Must be refrigerated to yield a shelf life of 1-2 yr
- Can tailor resin and foaming agent to yield the desired properties
- Can be formulated to reduce exotherm and the effects of the environment
- One trade name is Lucidol produced by Pennwalt Corp.

TABLE C-21. EPOXY SYNTACTIC FOAM

- Epoxy resin filled with microspheres
- Density - from 37-75 lb/ft^3
- Compressive strength - 6,300 psi
- Flexural strength - 4,950 psi
- Has not been used with aggregate
- Has similar properties to standard epoxy resin
- Available from Emerson & Cuming, Inc.

TABLE C-22. FURAN POLYMER CONCRETE

- Produced from byproducts of agriculture
- Two basic systems - furfulol alcohol
  furfurol acetone (Russian)
- Compressive strength - 6,000-8,000 psi in 1 hr
- Compressive strength approximately 500 psi per percent of resin to aggregate up to 10% resin
- High exotherm but reduced to workable quantity if resin content less than 10%
- Shrinkage - 1-3%
- Shelf life - > 2 yr
- Two component system
- Cure time - 10-20 min
- Quaker Oats Co.

TABLE C-23. WATER EXTENDED PHENOLIC POLYMER CONCRETE

- A crosslinkable phenolic resin in an aqueous dispersion
- Minimal environmental effects from wet weather
- Shelf life - 1 yr or more at 40°F
- Excellent adhesive properties
- Excellent wetting properties
- Low exotherm
- Strength data unavailable
- Several formulations with varying properties
- Developed by Union Carbide
- Has not been tested with aggregate

TABLE C-24. POLYESTER POLYMER CONCRETE

- Lb-183-13 polymer concrete (reinforced with fiberglass)
- Compressive strength - 12,000 to 16,000 psi
- Flexural Strength - 3,000 to 4,000 psi
- Cure time - 10-30 minutes
- Density - 70 lb/ft^3
- Cost - \$0.50 to \$0.70/ lb
- Shelf life - 6 months to 1 year
- Can be formulated to extend shelf life, viscosity, and improve safety
- No available data on the use of this material in an actual BDR experiment
- Produced by W.R. Grace Co.

TABLE C-25. URETHANE ELASTOMER POLYMER CONCRETE

- MOCA cured polyurethane
- Compressive strength - 2,000-5,000 psi
- Cure time - 5 minutes gel, 15 minutes cure
- Cost - \$.60 - \$.80/lb
- Density - 70-80 lb/ft^3
- Shelf life - greater than 1 year
- Exotherm high, but no thermal stress cracks result
- MOCA must be handled with caution because of toxicity and OSHA restrictions
- Could develop (formulate) a urethane with the desired properties
- Produced by RUCO Div. Hooker Chemical

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